A COURSE IN EXPERIMENTAL PSYCHOLOGY

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PART I: SENSATION AND PERCEPTION

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PREFACE.

THIS collection of experiments has passed through several stages and grown at every stage, until now Part I. is many times larger than the whole course as originally sketched, larger than any one is likely to use in its entirety, and almost too large to justify the title of a course at all. This I regret; but I take comfort in the thought that it will at least be easier for those who use the book to select what they need from it than from the sources from which it has been gathered. What a good laboratory course ought to include is not yet wholly clear, and can only be settled by trial; till this has been done a superfluous liberty of selection may not be wholly a disadvantage.

The experiments cover but a part of the experimental field, chiefly that of sensation and perception, though it is evidently impossible to take out any sort of mental phenomenon for entirely independent examination. In a subsequent volume, if I am able to prepare it, I shall hope to widen the course by chapters on voluntary movement, memory, attention, emotion, and other complicated mental states, in so far as they are open to experiments of moderate difficulty.

To some who turn its pages the book may seem rather a physiology of the special senses than a psychology of sensation and perception. This is not strange perhaps; but it should be remembered that the distinction between the two is not in the experiments themselves, but in the

perspective in which they are viewed. Whether or not the course is one in psychology or physiology must therefore be left in large measure to the user of it himself. In making the collection, I have tried to keep the line sharp in my own mind between those experiments that have a distinct psychological bearing, and those that do not; and while a considerable number of the latter have been included, they have been those that furnish data for other experiments, or are otherwise useful to the main purpose of the course. I trust that in this subordinate position they will not seem out of place.

Most of the experiments are demonstrational in character, and aimed at qualitative rather than quantitative results, even when for convenience they have been given a quantitative form. Precautions necessary for results of the latter sort have therefore been lightly touched upon. The setting of the experiments is generally the simplest, and the apparatus the least expensive, that promised satisfactory results. That no mistakes have been made, even from these points of view, is more than I can hope. I have been careful in the selection, however, and let the book pass from my hands with the hope that it may prove helpful both to those who have psychological courses to give and to those who shall by and by supplant it by a better one.

A few explanations are necessary with regard to particular portions of the book. The first six chapters remain, with the exception of insignificant changes, as they stood in the set of "advance sheets" printed in 1894. The literature from which they are drawn is therefore not later than the fall of 1893. I am sorry not to have brought them up to the date of the last three (the end of 1896), but to do so would have greatly delayed the completion of the work, if it had not prevented it altogether. The litera-

ture that has since appeared — some of it very important — can be followed in the excellent bibliographies of the *Psychological Review*, *Année Psychologique*, and *Zeitschrift für Psychologie*. A few points in the first six chapters had been marked for revision when opportunity offered. The more important of these have been taken up in the section of notes following the appendices (pp. 433 ff.). In three instances (pp. 16, 24, and 27) forward references to literature were made from earlier chapters to Chapter VIII.; but when Chapter VIII. came to be written, its plan was somewhat changed, and these references must therefore be cancelled.

The bibliographies include for the most part books and articles consulted in the preparation of the experiments. A few, however, have been merely scanned, and a very few have been taken at second hand. The purpose and scope of the bibliographies have been indicated more fully in the introduction to the first of them, p. 20.

It has been my intention by the references following the experiments to make full acknowledgment of my obligation to those from whom I have derived them. I may say here in addition, that, in the sense of wholly new experiments, there is hardly anything original in the book. My part in it has been one of selection and adaptation, and in the nature of the case could hardly have been anything else. Where obligations have been so great and to so many, it is difficult to choose for special mention, but mine have been very great to Helmholtz, Hering, Aubert, Wundt, Stumpf, and Goldscheider; and if what I say of the psychophysic methods is compared with Külpe's sections on the same subjects, it will be seen that I have taken advantage of his discriminating treatment of them. A good many of the diagrams used have of necessity been taken from the sources from which the experiments themselves

have been drawn, and are covered by the same references. For the loan of the blocks for several of the illusions in Chapter VII., I am indebted to the courtesy of Messrs. Charles Scribner's Sons and to Professor Joseph Jastrow; and for two of those showing disks for Weber's law, to Dr. August Kirschmann of the University of Toronto.

In a less tangible, but no less real way, I have been assisted by many of my colleagues in Clark University and elsewhere, and by many of my students, and here make grateful acknowledgment of the obligation. This is true especially with reference to President Hall, in whose lectures and seminary at Baltimore the study of several of the topics of this course was begun, and whose inspiration and encouragement have had much to do with its completion.

In the proof-reading and indexing I have been assisted by still others, whose unfailing helpfulness in other ways makes it seem strange to select this alone for mention.

E. C. S.

CLARK UNIVERSITY, *December*, 1897.

5. Judgments of Motion on the Skin. *a.* Let the subject close his eyes. Rest a pencil point or the head of a pin gently on his fore-arm and move it slowly and evenly up or down the arm. Require him to indicate his earliest judgment of the direction. If the experiment is carefully made, the fact of motion will be perceived before its direction.

b. Try a number of times, estimating the distances traversed in millimetres and averaging for the two directions separately. It will probably be found that the downward distances have been greater than the upward.

c. Starting from a fixed point on the fore-arm, move the pencil in irregular order up, down, right, or left, and require the subject to announce the direction of motion as before. Compare the results found with those found in Ex. 7.

Hall and Donaldson.

6. Feelings of Double Contact. *a.* If two parts of the body of like temperature are brought in contact, the two sensations do not blend, but the part that moves feels the one that does not; i.e., the sensations received by the moving part generally get more attention and are externalized. Try with the tips of the thumbs or fingers in contact. This general rule, however, has exceptions. Feel of the palm of the right hand first with the ball of the left thumb (which gives results in accord with the rule), then with the knuckle of the same thumb sharply bent. Light tapping of the forehead with the finger we feel in the forehead more markedly than in the finger, though usually with the hand on the forehead we feel the forehead.

b. If the parts are not of like temperature that which varies most from the normal bodily temperature will be felt by the other. Warm the right hand by holding it closed for a minute or two and then apply it to the forehead. The higher temperature will be perceived by the forehead, while

at the same time the hand as the more expert touch organ will perceive the form of the forehead. Cool the right hand by holding it a few minutes in cold water, dry it and apply it to the back of the left hand. The right hand may seem to be feeling of a cold left hand. In this case of course both the temperature and form feelings are credited to the right hand. If the temperature is not very different the direction of attention may dictate which shall be felt by the other.

Weber, 556–559; Dessoir, 229.

7. Weber's Sensory Circles. *a.* Find the least distance apart at which the points of the æsthesiometric compasses[1] can be recognized as two when applied to the skin of the fore-arm. Try also the upper arm, the back of the hand, the forehead, the finger-tip, and the tip of the tongue. Be very careful to put both points on the skin at the same time and to bear on equally with both. Cf. Weber's measurements as given in the text-books; also Goldscheider's (quoted by Ladd, p. 411).

b. Compare the distance between the points just recognizable as two when applied lengthwise of the arm with that found when they are applied crosswise. Compare the results found in *a* and *b* with those found in Ex. 5, but remember that this compass experiment requires the discrimination of the points.

c. Give the points a slightly less separation than that found for the fore-arm crosswise, and beginning at the elbow draw the points downward side by side along the arm. They will at first appear as one, later as two, after which they will appear to separate as they descend. Something similar will be found on drawing the points from side

[1] For the apparatus needed in this and later experiments, see the list and descriptions in the chapter on apparatus below.

to side across the face so that one shall go above, the other below the mouth.

d. Make the skin anæsthetic with an ether spray and test the discriminative sensibility as before.

Weber, 524–530, 536–541; Goldscheider, *B*, 70 ff., 84 ff.

8. Filled Space is relatively under-estimated on the skin. Set up in a small wooden rod a row of five pins separated by intervals of half an inch, and in another two pins two inches apart. Apply to the arm like the compasses above. The space occupied by the five pins will seem less than that between the two. A still simpler way given by James is as follows: Cut one end of a visiting card into a series of notches, and the other into one long notch so as to leave two points as far apart as the outer points at the other end, but separated by an empty interval. Apply to the skin as before. This illusion, though very clear for some experimenters, does not seem equally so for all, and some have difficulty with it.

James, II., 141, footnote.

9. Active Touch is far more discriminating than mere contact. Compare the sensations received from simply resting the tip of the finger on a rough covered book with those received when the finger is moved and the surface "felt of."

10. The Time Discriminations of the sense of contact are very delicate. Strike a tuning-fork; touch it lightly, and after about a second remove the finger so as not to stop the fork. The taps of the fork on the skin do not blend into a smooth sensation even when the vibrations are several hundred a second. One may assure himself that the touching does not much alter the rate of the fork by using another that beats with the first. If the touching is carefully done,

the rate of the beats will not be noticeably altered. (On beating forks see Chap. IV.) The roughness may also be felt but not so strongly, by setting the stem of the fork upon the skin. The roughness of the pulses of air from large tuning-forks can also be felt when the hand is brought near, but not into actual contact with them.

Wittich, 335 ff.; Schwaner; Sergi.

11. After-images of Touch. Touch the skin of the wrist lightly with the point of a needle, and notice that beside the original sensation, there is, after a more or less free interval, a second pulse of sensation. The interval is brief, a second or under, and the sensation appears to come from within. In quality it is like the first, but without the pressure component. The prick of the needle point is not essential; the second sensation can be observed when the head of a pin is applied. Too hard touches must be avoided in testing for these images, as they give rise to a continuous after-image that fills the interval. The second image is apparently due to a double conduction in the spinal cord, and is therefore different from the after-images of the other senses. A portion of the original excitation is conveyed in the posterior columns of the cord to the cortex. Another portion goes by a slower path through the central gray matter of the cord. Cf. Ex. 32.

Goldscheider, *II*, 168 f.

12. An Interesting Illusion of Length, based on the time during which a touch sensation continues, may be observed as follows: Require the subject to close his eyes. Take a piece of coarse thread a couple of feet long and make a knot in the middle of it. Place the knot between the thumb and forefinger of the subject, asking him to press it gently. Then draw the thread slowly through between his thumb and finger and ask him to estimate its length. Repeat the

process, this time drawing it rapidly. The drawing must not be too slow in the first case nor too fast in the second, or the nature of the illusion may be suggested to the subject and more or less completely corrected.

Loeb, 121–122.

For Minimal Contact in relation to Pressure, see Ex. 22; in relation to Tickle, see Ex. 31.

SENSATIONS OF TEMPERATURE.

13. Warm and Cold Spots. *a.* Move one of the pointed brass rods, or even a cool lead-pencil, slowly and lightly over the skin of the back of the hand. At certain points distinct sensations of cold will flash out, while at others no temperature sensation will be perceived, or at most, only faint and diffuse ones. Heat one of the rods slightly in the gas flame and repeat the experiment. More care will be required in locating the warm spots than the cold spots, for their sensations seem less distinct.

b. On some convenient portion of the skin mark off the corners of a square 2 cm. on the side. Go over this square carefully both lengthwise and crosswise for both warmth and cold, drawing the point along lines 1 mm. apart, and note on a corresponding square of millimetre paper the warm and cold spots found, warm spots with red ink, cold with black. This time the points should be heated or cooled considerably by placing them in vessels of hot or cold water, and should be kept at an approximately constant temperature by frequent change, one being left in the water while the other is in use. Break the experiment into a number of sittings so as to avoid fatiguing the spots, for they are very easily fatigued. A map made in this way cannot hope to represent all the spots, but it will suffice to show the permanence of some of them and possibly to show a little their general arrangement. When the map has been made, select a responsive

and isolated cold spot, and try it with a warm point. Try a similar warm spot with a cold point.

c. Notice the very distinct persistence of the sensations after the point has been removed, that is, the temperature after-images.

An interesting question suggested by this punctual location of temperature sensations is this, namely: How does it come about that we ordinarily conceive such sensations as continuous over considerable areas.

Blix; Goldscheider, *A*, *B*, *E*; Donaldson.

14. Mechanical and Chemical Stimulation of the Temperature Spots.[1] The temperature spots respond with their characteristic sensations to mechanical and chemical stimulation (and some observers find also, to electrical stimulation), and do not give pain when punctured.

a. Choose a very certainly located cold spot and tap it gently with a fine wooden point (not too soon after locating it, if it has been fatigued in locating); or better, have an assistant tap it. Thrust a needle into a well-located cold point. Try both for comparison on an adjacent portion of the skin.

b. Choose a convenient area, say, on the back of the hand or the temple, and rub the skin lightly with a menthol pencil. After a little the sensation of cold will appear. Goldscheider's tests with a thermometer applied to the skin show that the sensation is not due to an actual cooling of it. The menthol makes the nerves of cold at first hyperæsthetic (so that they respond with their specific sensation to

[1] Such experiments as these illustrate the Law of the Specific Energy of Nerves, which may be stated somewhat as follows: Every stimulus that can excite a sensory nerve at all, causes such sensations as follow the stimulation of that nerve in its customary way and only such. As regards the interpretation to be put on the phenomena thus generalized there is dispute. Goldscheider *I*; Wundt, 3te Aufl. I. 332 ff., 1te I. Aufl. 323; Helmholtz, Sensations of Tone, 148; Optik, 2te Aufl. 233, 1te Aufl. 193; Ladd, 307, 353.

mere contact, and give an intenser sensation when a cold body is applied than do adjacent normal portions of the skin); afterward, however, all the cutaneous nerves become more or less anæsthetic.

c. Chemical stimulation of the heat nerves can be tested with CO_2. Provide two like vessels; place them side by side and fill one with CO_2. Plunge the hand into the vessel containing the gas, and for comparison into the one containing air. For the additional experiments necessary to prove this to be a real chemical stimulation, see the literature.

Blix, Goldscheider *A*, *B*, *D*, *F*, and Donaldson; on c, R. Du Bois-Reymond.

15. The Temperature of the Skin at any moment is a balance between its gain and loss of heat. Anything that disturbs that balance, causing increased gain or loss, produces temperature sensations. It is common experience that a piece of cloth, a bit of wood, a piece of metal, all of the same temperature as the air that seems indifferent to the hand, cause different degrees of the sensation of cold when touched, because they increase the loss of heat by conduction in different degrees. If a paper bag be placed over the hand held upward, a sensation of warmth is soon felt, because of the decreased loss of heat.

16. The Shifting of the "Physiological Zero." *a.* Provide three vessels of water, one at 30° C., the second at 40°, the third at 20°. Put a finger of one hand into the warmer water, a finger of the other into the cooler. At first the usual temperature sensations will be felt, but after a little they disappear more or less completely, because of the fatigue of the corresponding temperature organs. Now transfer both fingers to the water of normal temperature. It will seem cool to the finger from warmer water and warm to the one from cooler. This experiment has been sometimes regarded as one of successive contrast.

b. Hold the hand for one minute in water at 12° C., then transfer it to water at 18°. The latter will at first feel warm, but after a time cold again. The water at 18° first causes a decrease in the loss of heat or a slight gain. but later a continued loss.

Weber; Hering; Goldscheider, *B*, 32 ff.

17. Effect of Extent of Surface Stimulated. The intensity of the sensation increases as the stimulated area increases. Dip the right forefinger (or hand) into hot or cold water, observe the sensation, and immediately insert the other forefinger to an equal depth. Vary the experiment by inserting the left finger first, and by inserting both at once and then withdrawing one. The original experiment of Weber, who inserted first a finger, and then the whole of the other hand, gives striking results, but has the fault, as Goldscheider rightly observes, of adding a more sensitive as well as a larger area. This experiment must not be inconsiderately contrasted with Ex. 23.

Weber, 553; Goldscheider, *C*, 475–476.

18. Temperature Fatigue. *a.* Extreme temperatures fatigue the sensory apparatus of both heat and cold. Hold a finger in water at 45° C., the corresponding finger of the other hand in water which feels neither cold nor hot (about 32°). After 30 seconds dip them alternately into water at 10°. The finger from the water at 32° will feel the cold more strongly. Hold a finger in water at 10°, the corresponding finger of the other hand in water at 32°. After 30 seconds dip them alternately in water at 45°. The finger from the water at 32° will feel the heat more strongly.

b. The fatigue of the temperature apparatus may produce an apparent contradiction of Ex. 17. Plunge one hand entirely under cold water and keep it there for a moment. Then dip the finger of the other hand or the whole hand

several times in the same water, withdrawing it immediately each time. The water seems colder to the finger or hand which is only dipped.

Weber, 570; Goldscheider, *B*, 34 ff.

19. Temperature After-images. *a.* Hold a cold piece of metal on the forehead or on the palm of the hand for half a minute. On removing it the sensation of cold continues, though the actual temperature of the skin is rising. Sometimes fluctuations are observed in the persisting sensation. After contact with a hot body the sensation of heat continues in the same way, though the temperature of the skin falls. Goldscheider explains this result for cold in part by the persistence of the cold sensation in the manner of an after-image, and in part by the lessened sensibility of the nerves of heat; a similar explanation *mutatis mutandis* holds also for heat.

b. Intermittent after-images, or those that recur after an interval more or less free of sensation, have been observed especially with repeated stimulation. Heat a key till it is just a little short of painfully hot, touch some part of the skin, e.g., the wrist, three or four times at intervals of about half a second. The after-image of the heat will appear several seconds later. Try the same for cold, but use a key that is at the temperature of the air.

Cf. Ex. 13 *c.*, also the after-images of hearing and vision, Chapters IV. and V., and notice that all the temperature after-images are positive; i.e., like the original sensation.

Goldscheider, *B*, 11, 34 ff., 38; on *b*, Dessoir, 300.

20. Fineness of Temperature Discrimination. *a.* Find what is the least perceptible difference in temperature between two vessels of water at about 30° C., at about 0°, and about 55°. The finest discrimination will probably be found with the first mentioned, if the discrimination does

not prove too fine at all these points to be measured with the thermometers at hand. Use the same hand for these tests, always dipping it to the same depth. It is better to dip the hand repeatedly than to keep it in the water.

b. The different surfaces of the body vary much in their sensitiveness to temperature. The mucous surfaces are quite obtuse. When drinking a comfortably hot cup of coffee, dip the upper lip into it so that the coffee touches the skin above the red part of the lip, or dip the finger into it; it will seem burning hot. Plunge the hand into water at 5–10° C. The sensation of cold will be strongest at first on the back of the hand where the skin is thin, but a little later will come out more strongly in the palm, where it will continue to be stronger and may finally approach pain.

c. The middle line of the body is less sensitive to temperature than portions at either side of it. Touch the middle of the forehead, or the tip of the nose, with a piece of warm or cold metal and then touch several places to the right and left of that point.

Fechner; Weber, 552 ff.; Goldscheider, *B*, 49 ff.

SENSATIONS OF PRESSURE.

21. Pressure Points. Make an obtuse but extremely fine cork point (pyramidal in shape; for example, the pyramid a quarter of an inch square on the base and of equal height), set it upon the point of a pen or other convenient holder, or use a match whittled down to a fine point, or even a needle. Choose an area on the fore-arm and test for its pressure spots somewhat as for the hot and cold spots, but this time set the cork point as lightly as possible on point after point of the skin instead of drawing it along. Two kinds of sensation will be felt; at some points a clear feeling of contact with a sharp point will be felt, at others no feeling at all, or

a dull and vacuous one. The first are the pressure points. Goldscheider describes their sensations on light contact as "delicate," "lively," "somewhat tickling . . . as from moving a hair;" on stronger pressure, "as if there were a resistance at that point in the skin, which worked against the pressure stimulus;" "as if a small hard kernel lay there and was pressed down into the skin."

The first are said to be more sensitive to small changes of pressure, and though with sufficient increase both give pain, their sensations retain their characteristics. They are closer together than the temperature spots, and harder to locate. The fact that our most frequent sensations of pressure are from surfaces and not from points is perhaps the reason it is difficult at first to recognize a pressure quality in these sensations.

Goldscheider, *B*, 76 ff.

22. Minimal Pressure or Simple Contact. Find weights that are just perceivable on the volar side of the fore-arm and on the tips of the fingers. Try also, if convenient, the temples, forehead, and eyelids. In applying the weights, see that they are brought down slowly upon the surface of the skin, that they touch equally at all points, and that their presence is not betrayed by motion of the weight after it touches the skin. This can be done by using a penholder or small rod, with its tip put through the ring of the weight, for laying it on. Compare the relative sensibility found by this method with that found with Weber's compasses for the same parts (Ex. 7) and note that the latter requires discrimination, not mere perception. See also Exs. 29 and 31.

Aubert and Kammler; Bloch.

23. Relation of Apparent Weight to Area of Surface Stimulated. Test with the equal weights of unequal size

upon the hand, properly supported to exclude "muscle sense." The smaller will seem decidedly heavier.

24. Discriminative Sensibility for Pressures. Use the pressure balance if one is at hand; if not, have the subject close his eyes and lay his hand, palm upward, on such a support as will bring his arm into a comfortable position and make his palm level; for example, on a folded towel placed on a low table or the seat of a chair. (The matter of an easy position for the subject is of cardinal importance in all psychological experiments.) The method of experimenting here to be used is that of the "Just Observable Difference" or "Minimal Change;" it may be applied as follows: Lay in the subject's palm a piece of thick and soft blotting-paper just large enough to prevent the weight from touching the skin. Place the standard weight of 100 grams upon the paper and allow it to remain a sufficient time for the subject to get a clear perception of its weight. Then remove it and immediately put in its place a weight of 110 grams, allowing that to remain as long as the first. If the subject can recognize this difference easily and surely, try him with 109, 108, and so on, alternating the standard weight and a weight to be compared with it till a weight is found that is just recognizably different from the standard. If 110 grams is not recognizably different, take 111, 112 instead of 109, 108. Occasionally follow the standard with another 100 gram weight to guard against illusion on the part of the subject. After having determined the just observably greater weight, find the one that is just observably lighter in the same way. Make a good number of determinations of these just observably heavier and lighter weights, sometimes going toward the standard and sometimes away from it. Take the differences between them and the standard weight and average the results. The ratio of this average to the standard will be a measure of the dis-

criminative sensibility required. If, for example, the ratio for one subject is 7 : 100 and for another 14 : 100, the first has a sensibility to pressure differences twice as acute as the second. In half of the tests, both above and below, the standard weight must be placed upon the hand first, and in half the weight to be compared with it. It is well also to distribute the determinations of the differences above and below so that they shall be about equally affected by practice and fatigue. The aim should always be to keep all the conditions of the experiment as constant as possible and especially to have them the same for the weights to be compared. Be careful in putting on the weights that the subject does not recognize a difference in the force with which they strike; also that suggestions by difference of temperature or by sounds made in selecting the weights are avoided.

It is easy to see that this method has some disadvantages. First, it leaves to the feeling of the subject what the just observable difference is, and this feeling is liable to change from subject to subject and in the same subject at different times. In using this method the subject must know the direction of the change that he is to recognize, and so is somewhat exposed to the influence of expectant attention. And finally, when weights are found that are just observably different, it is possible that they are a little larger than the subject could just recognize; that is, that he has allowed himself a small margin for security. These difficulties may be partially obviated by a more rigorous application of the method.

Thus in making the tests for the just observable differences above and below, weights must first be taken that are not recognizably different from the standard, and must then be slowly increased or decreased till just observably different. Subjective equality must be regarded rather than objective

equality, if the two are at odds, as sometimes happens. To these tests two others must be added; namely, for the just *un*observable differences above and below, the operator now selecting a weight that is clearly heavier than the standard and decreasing it gradually till it can just no longer be recognized as different, and similarly selecting one that is at first clearly lighter than the standard and increasing it till it seems the same. The average of the four tests, just recognizably different and just *un*recognizably different, is then taken for the ratio. When great accuracy is required the method must be used in this complete form. For other methods and fuller literature, see the chapter on Weber's Law below.

Weber, 543–549; Wundt, 3te Aufl., I., 343 ff., 350; 4te Aufl., I., 336 f., 341 ff.

25. Temperature and Pressure. Cold and hot bodies feel heavier than bodies of equal weight at a normal temperature.

a. For cold, take two dollar pieces, warm one until it ceases to seem cold; cool the other to 10° C. Apply alternately to the palm of the hand, letting the hand rest, meanwhile, on the table or some other support so as to exclude "muscle sense." The cold one will seem much heavier, perhaps as heavy as two at the normal temperature. The same experiment may be tried on the forehead with the head supported.

b. For heat take two wooden cylinders of equal weight; heat one to a high temperature by standing it on end in a metal vessel floating in a water bath. Apply the cylinders on end alternately to the back of the hand (supported) between the metacarpal bones of the thumb and first finger. The hot one will seem heavier.

Weber, 512, 551; Szabadfoeldi; Funke, 320; Dessoir, 304–306.

26. Pressure Evenly Distributed over a Considerable Area is less strongly felt than pressure upon an area bordered by

one that is not pressed. Dip the hand up to the wrist into water (or, better still, into mercury) of normal temperature, and notice that the sensation of pressure is strongest in a ring about the wrist at the surface of the water; possibly stronger on the volar than on the dorsal side. The ring effect is unmistakable when the hand is moved up and down in the water.

27. Pressures are not Equally well Perceived in all Parts of the Body. This may be tested with weights applied somewhat as in Ex. 24, as was done by Weber, but a simpler experiment may be made as follows: Find the pulse at the wrist; feel it with the finger tips, the back of the fingers, the side of the hand, the other wrist, the lip, and the tip of the tongue. Try the pulse in the temple with the finger tips, the side of the hand, and the fore-arm. Notice that when it is felt by another person the experimenter is unable to feel it subjectively.

Goltz.

28. Refinement of Active Pressure Sense. Something of the refinement of the pressure sense in perceiving the unevenness of surfaces may be found by laying a hair on a plate of glass or other hard, smooth surface and over it 10 or 15 sheets of writing-paper. The position of the hair can easily be felt by passing the finger tips back and forth over the paper.

29. The Hairs as Organs of Touch. The finest hairs respond with a distinct sensation of anticipatory touch, when they are moved, and probably this accounts for a part at least of the differences between the fore-arm and finger tips found in Ex. 22. Touch a few single hairs and observe the sensation.

Blaschko.

30. The Feeling of Traction or Negative Pressure has

been discriminated by some authors, but has rarely been made an object of experiment. It is to be observed when viscid substances are handled, when a portion of the skin is brought over the mouth of a closed vessel and the air exhausted, or when in any other way the skin is lifted from the underlying portions of a member. The sensation may be studied qualitatively by passing a thread through a small bit of court-plaster, knotting it on the gummed side and sticking the plaster to the skin. Traction on the thread now produces the sensation.

Hall and Motora, 93 ff.; Bloch.

GENERAL SENSATIONS, TICKLE, AND PAIN.

These topics, though clearly of very great psychological interest, have so far received comparatively little careful study, and few experiments have been made upon them. They are not exclusively dermal senses, but the skin offers the most convenient field for the study of the two to be considered here, namely, tickle and pain. In both the experimenter should notice the subjective cast of the sensations. Our eyes and ears give us information about colored and sounding things, but tickle and pain let us know that *we* are being tickled or hurt by something.

31. Tickle. Two sorts of tickle are easily distinguishable, a deep-seated tickle located in the rib region, which seems more strongly developed in children, and responds to rather strong stimulation, and a superficial tickle much more widely distributed, and responding to slight stimuli only. The latter sort is that regarded in this group of experiments.

a. Touch very lightly the different parts of the face, especially about the eyes, the margin of the lips and the opening of the ears with the tip of a light wisp of paper and notice the tickle sensations. Notice the apparent

disproportion between the stimulus and the resulting sensation, the wide and indefinite irradiation, and the long after-image.

b. Touch the same parts as lightly as possible with the tip of a penholder or the finger, and then with the same instrument while exerting at the same time a moderate pressure. Notice the difference in effect; notice also that the tendency to rub a tickled surface is a tendency to use a greater stimulus to remove the effects of the less. Notice also, when feeling a tendency to sneeze, that the sneeze can be wholly prevented by firm pressure or rubbing of the sides of the nose or the adjacent parts of the face.

c. Tickle is apparently a summation phenomenon. Touch the tip of the tongue lightly with the prong of a tuning-fork at rest and notice the after-image, which, however, has no tickle in it. Then strike the fork and touch it to the tip of the tongue. Compare the effects.

d. The ticklability of adjacent parts of the body is quite markedly different. Test with the tuning-fork, striking it and applying it gently to the tip, sides, and middle of the upper surface of the tongue and to the lower surface.

32. Pain. *a*. Slow conduction. Remove the shoe and strike a smart blow with a light rod on the sole of the foot. or on a corn; the pain will be perceived noticeably later than the first sensation of contact, separated from it perhaps by an almost empty interval. This delay is probably due to the same cause as the secondary after-image of touch in Ex. 11.

b. Temperature pains. A given increase of heat above the blood temperature is more effective in causing pain than an equal decrease. Compare the effects of plunging the hand into water at 10°C. and at 60°. Use a considerable quantity of water and do not allow the hand to remain too

long in the water, for its sensibility to pain as well as to temperature is decreased by fatigue.

Experiments on pain can likewise be made with electrical stimulation and pressure. These are especially suitable for determining the relative sensibility of different subjects. The first can easily be tried with the sliding induction coil, by applying the electrodes to the surface to be tested and then gradually pushing the secondary coil towards the primary till the stimulation becomes painful. For apparatus, see the chapter on apparatus below.

Weber, 569 ff.; Dessoir, Beaunis, Lombroso, Mantegazza, Preyer, 89.

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CHAPTER II.

Kinæsthetic and Static Senses.

THIS group of senses furnishes us data for the perception of the positions and motions of our members and of the body as a whole, and plays a leading part in the perception of space. It includes some senses whose existence or efficiency is disputed (Innervation Sense[1] and Muscle Sense), and others whose independence has only of late been generally recognized (Joint Sense and Tendon Sense). All are closely united with one another and with pressure and contact, and some are hardly ever dissociated except by disease. This chapter is necessarily limited to the experimental side of the subject and to the simpler experiments to be found there. Many of the most important psycho-

[1] The term "innervation sense" must not be taken too strictly as meaning a wholly independent sense of motor discharge, as it has often been taken. Says Wundt, in his last edition (4te Aufl. I., 425): "Manifold observations make it probable that the central components of the sensations accompanying active movements have their origin in the memory-images of movements previously executed, which partly initiate, partly accompany, each voluntary movement. Since memory-images possess qualitatively the same sensory content as the original perceptions, such central sensations of effort and movement (*Kraft- und Bewegungsempfindungen*) will under normal conditions blend completely with the more intense peripheral sensations of the same kind; they will, however, produce an independent effect, if from any cause the peripheral sensations fall away. It would be proper, therefore, to give up the term "innervation sensations" for the sensations in question; because it is liable to convey the false impression that these are sensations which in and for themselves, without any relation to the peripheral components of the sensations of effort and movement, accompany the motor innervation. This assumption, which as a rule has formerly been connected with the notion of "innervation sensations," is, however, very improbable." Cf. also p. 431, and in the third edition I., p. 405 ff.

logical problems involve the motor sensations of the eye, some of which are considered in Chap. VII.

Muscle Sense, *Kraftsinn.*

Whether there are any specific muscular sensations distinct from those that come from other parts of the member in motion cannot now be asserted with positiveness; but even if there be such, the part that they play in our ordinary motor perceptions is probably a minor one. The term "muscle sense," however, has been used to designate the whole group of motor sensations, and is here retained for that purpose.

33. Lifted Weights. *a.* Weights lifted slowly seem heavier than the same weights lifted rapidly. Lift the same weight twice, lifting it first at the most natural and convenient rate, and the second time very slowly, beginning with much less than the necessary effort and gradually increasing it till the weight rises.

b. Lift a moderate weight with one hand and at the same time clench the other sharply. The weight will seem lighter than when no simultaneous effort is made.

c. Repeat Ex. 23, using active lifting instead of pressure in comparing the weights.

Charpentier; on *a*, Goldscheider, *A*, 186.

34. Discriminative Sensibility for Lifted Weights.

a. Find by the method of experiment used in Ex. 24 what is the just observable difference above and below a standard weight of 100 grams, when the weights are lifted instead of merely being allowed to press upon the skin. In this experiment lift the weights successively with the same hand. The weights must be placed near together within convenient reach, and care must be taken that both are lifted at the same rate and to the same height. Let the subject lift one

weight and then the other, and render his decision after once lifting each. In half of the trials let the standard weight be placed at the left side of the weight to be compared and be lifted first; in the other half let the weight to be compared stand at the left and lead in the lifting.

b. Repeat the experiment, letting the subject lift the standard with one hand, and the comparison weight with the other, keeping the same hand for each during each set of trials (that is, during a determination of the just observable difference above and below), but combining a number of sets with the standard in the right hand with an equal number in which it is in the left. Find also from the figures the ratios when the standard is in the right hand and when it is in the left hand, for use in Ex. 35. Compare the ratios found in these experiments with that found in Ex. 24.

In these experiments the sense of pressure might be expected to co-operate; but when it is excluded, or put at a relative disadvantage, the sensibility for differences of lifted weights is not diminished. Weber's method of excluding the pressure sense was to wrap the weights in pieces of cloth, and lift them by the four corners together. The pressure on these corners can be changed at will, irrespective of the heaviness of the weight lifted.

For fuller literature on lifted weights, see the chapter on Weber's Law below.

Weber, 546–547; Müller und Schumann; James, II., 189 ff., 486 ff.: Beaunis; Wundt; Fullerton and Cattell.

35. Adjustment of the Motor Discharge. After having performed the second part of Ex. 34, compare the standard weight with a very much heavier weight, e.g., 2 kg., with all the circumstances of actual careful judgment. Practise this judgment thirty times, leaving a longer time between

the individual comparisons than between liftings of the weights compared. Then at once return to the smaller weights, giving the standard to the same hand as before, and to the hand that has just been lifting the 2 kg. the weight to be compared. Not only will the weight just recognizably heavier before seem considerably lighter than the standard, but also still heavier weights will seem so. This time the tests must be few, not more than three or four. If more tests are desired, practise the comparison of the standard and 2 kg. weight again ten times before taking them. By the practice the nervous centres discharging into the muscles that raise the 2 kg. weight become accustomed to a larger discharge than that required for the small weights and do not at once re-adapt themselves, but supply too great a discharge. The weight now rises with greater rapidity than the standard, and is consequently pronounced lighter (Müller and Schumann), or the balance between the extensors and flexors that was suited to raising the heavier weight is not suited to the lighter weight, and the second is pronounced lighter because of the strain in the extensors necessary to restore the balance (Delabarre). This experiment seems conclusive against a well-developed and independent innervation sense; for if there were any sensation of nervous discharge, we ought to know when we go from a very heavy to a light weight that the discharge is disproportionate; but we do not.

Müller und Schumann; but cf. also Fullerton and Cattell, 131, and Delabarre.

INNERVATION SENSE.

36. Simultaneous Movements. The evidence most frequently offered in support of a special innervation sense is clinical and therefore beyond the scope of this course. Experiments of the type of the following have been brought forward, but their interpretation has been disputed.

a. Stand erect before the blackboard, with the eyes closed and coat off, if it interferes with free motion of the arms. Draw with each hand, using both at once, a conventional leaf pattern like those in the annexed cut, drawing always from *a* to *b*. In drawing, try to make the lobes of the leaf of equal size, like those in Fig. 1; draw each with a single simultaneous "free-hand" motion of the arms, that is, draw each with a single volitional impulse directed equally to the two sides; the last point is important. First draw a pair of leaves, beginning them with the hands before the shoulders at the same height; the result will be approximately like Fig. 1. Next draw a pair with one hand about a foot higher than before, the other about a foot lower; the result will be like Fig. 2.

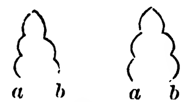


Fig. 1.

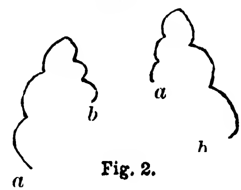


Fig. 2.

b. Bring the hands again to the position used in drawing Fig. 1, and draw a pair of leaves having their apices right and left. The leaves will be symmetrical. Next begin with one hand about a foot farther away from the median plane than before and the other at it, but both at the same level. Draw as before; asymmetrical leaves will be the result. Repeat the drawing a number of times, sometimes raising or extending one arm, sometimes the other. In general it will be found that, notwithstanding the intention to make equal movements of the hands, the motions of further extension in the extended arm and of further flexion in the flexed arm are too short, and those in the contrary direction in each case too long. The argument founded on this experiment runs as follows: We think that our hands execute equal movements, when they do not, because we are conscious of willing equal movements, and unconscious, or only

inexactly conscious, of those actually made. If we perceived motion of our members by the skin, joint, and muscle sensations that accompany their motion (as the opponents of the innervation sense believe) we ought to know the extent to which our hands are moved each time, and not to fall into the illusion that we find in these experiments. Cf. Ex. 44 *d*. 2, 418

Loeb, *B*, 15 ff.

37. Illusory Movement in an Immovable Member. Lay the hand palm downward on the edge of the table or on a thick book so that the last three fingers shall be supported and held extended while the thumb and first finger remain free. Bend the first finger considerably at both the inner joints, and hold it in position with the other hand. The finger-tip is still movable, as will be found on touching it; but it is anatomically impossible to move it voluntarily. When, however, the effort is made to move it (the eyes being closed), there is a sensation of motion, though no actual motion is possible. From this, an inner sense of motion (innervation sense) has been inferred. When operating upon another subject, the operator may hold the finger in position, and require the subject to execute with the corresponding finger of his free hand a motion equal to that which he thinks he makes with the one that is held. Observe, however, that the tendons in the wrist move, and that there are slight movements elsewhere in the hand.

Sternberg; James, II., 105, 515, footnote; Goldscheider, *A*, 317.

38. Ferrier's Experiment. That the feeling of effort is largely, if not entirely, of peripheral rather than central origin, appears from such experiments as the following. Hold the finger as if to pull the trigger of a pistol. Think vigorously of bending the finger, but do not bend it; an unmis-

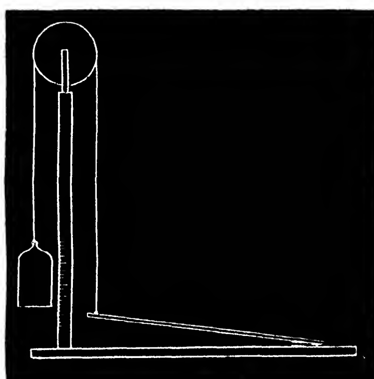
takable feeling of effort results. Repeat the experiment, and notice that the breath is involuntarily held, and that there are tensions in other muscles than those that would move the finger. Repeat the experiment again, taking care to keep the breathing regular and the other muscles passive. Little or no feeling of effort will now accompany the imaginary bending of the finger.

Ferrier, 382 ff. (English Ed.).

On Innervation Sense in general, besides the authors already mentioned, see: Wundt, 3te Aufl. I., 397 ff., 4te Aufl. I., 423 ff.; James, II., 486 ff.; Goldscheider, *A*, 206 ff.

Sensations of Motion, Joint Sensations.

39. Passive Motion at the Elbow. Let the subject rest his fore-arm flat upon the arm-board of the instrument (bringing his elbow over the hinge), and close his eyes. Let the operator then raise or lower the free end of the arm-board slowly by pressing down or lifting the counter weight, and require the subject to announce when he first perceives the motion of his fore-arm. Record the angular movement required to produce a just observable sensation. Notice that the movement seems to be located chiefly in the hand. It is extremely important not to mistake the sensation of increased pressure or of jar for that of motion. The rate of movement will be found important, and should be



kept as constant as possible. The results found in this way are rough; for more exact methods see Goldscheider, *A.*

40. Active Movement of the Last Joint of the Finger. The joint sensations of the fingers are less fine than those of the elbow, but are more convenient for demonstration of active flexion. Fasten a piece of straw, with court-plaster or otherwise, to the finger-nail of the middle finger, and cut it off at such a length that the distance from the joint of the finger to the end of the straw shall be 115 mm. With that radius 2 mm. corresponds to about 1° of angular measure. Rest the hand on a thick book, letting the last joint of the finger extend beyond the edge. Set up a millimeter scale at right angles with the straw. Close the eyes and make the least possible flexion of the finger at the last joint, having an assistant note its extent on the scale. Close attention may perhaps be able in both the active and passive movements to locate the sensation in the joint, but more rigorous experiments are required to show its character clearly, and to prove its location.

Goldscheider, *A.*

41. Location of Movements. *a.* Motions on the skin can be interpreted either as the movement of an object over the surface of the skin, or of the skin over the surface of the object. This opens the way for illusions. Have an assistant draw a pencil-point gently across the wrist or the finger-tips of the observer, who sits with closed eyes. A tendency to interpret the sensation as motion of the wrist or finger will be observed. The hand and arm must be held free, so that the illusion may not be corrected by the presence of other touch sensations.

b. With the eyes closed, move the wrist or finger over a stationary pencil-point. In this case the point also seems to be in motion in a direction contrary to that of the hand.

c. When the movement may be interpreted as belonging to either of two members, it may be credited to the more mobile of the two, or may be shared by both. Rest the finger lightly on the forehead; then, taking pains to keep its position fixed, move the head from side to side. There is a strong tendency to credit the motion to the finger and arm. Hold the last three fingers close together, and move the first away from them and toward them again. All will seem to move, but the last three in an opposite direction to the first.

d. Ex. 4 above is an experiment on the location of movements as well as of touches. If the cane is swung so as to describe the surface of a cone we are conscious of the path described by its point, as well as that of the hand holding it.

Cf. Ex. 39 where the motion of the whole fore-arm and hand is credited chiefly to the latter.

Vierordt; on *c*, Goldscheider, *A*, 181 ff.

42. Interrupted Extent may seem smaller to a moving member than uninterrupted. In a piece of cardboard make three pin-holes in a line separated by spaces of an inch and a half. Fill one of the spaces with pin-holes a quarter of an inch apart. Turn the card over, close the eyes, and move the finger-tip across the little eminences made by the pin-holes. The illusion seems more marked when the finger moves over the interrupted half of the line first. Examine the card visually, and notice that the visual illusion is in the directly opposite sense. As in the similar touch experiment above (Ex. 8) the results are apparently not equally clear for all observers.

James, II., 250.

SENSATIONS OF RESISTANCE.

43. Illusory Resistance. *a.* Hold a heavy weight by a string so that it hangs, with the arm extended, a few inches

above the floor, or better, have the string placed in the hand by an assistant so that the length of the string may not be known beforehand. Lower the weight rather rapidly till it rests on the floor or other support. As it strikes, a sensation of arrest will be perceived, somewhat as though the hand were suddenly supported by a light rod. The illusion is even more marked when the string, instead of being held in the hand, is fastened to a small rod, and that is held. The disturbing noise of the weight may be obviated by having it come to rest on a cushion or in a box of sand. The illusion is due to the unexpected strain put upon the muscles that lower the arm by the tension of those that have been holding the weight. This feeling of arrest is probably a joint sensation. To distinguish this sensation from the motion sensations of the joints, Goldscheider has called it a "joint-pressure sensation."

b. When the movement of the rod is continued downward beyond the point at which the sensation of arrest is felt, a certain difficulty of movement may still be observed, as though the rod were moving through a resisting medium. This sensation Goldscheider distinguishes from the sensation observed in *a*, believing it to be the true sensation of difficult motion (of weight and heaviness also) and crediting it to the tendons.

c. Notice something similar to *b* in pouring a quantity of mercury rapidly from one vessel to another.

It is evident that such illusions as these speak against the existence of an innervation sense in the common acceptation of the term.

Goldscheider, *A*, 164 ff., 172 ff., *D*; on *b*, *A*, 188; Mach, *A*, 70 ff.

Bilateral Asymmetries of Position and Motion.

44. Apparently Symmetrical Motions of the arms. In all the tests of this group, the subject should be kept in ignor-

ance of the nature and amount of his errors till the tests are finished.

a. Hold an ordinary cork between the thumb and first two fingers of each hand. Close the eyes and bring the two corks together at arm's length in the median plane before the face, having an assistant note the approximate amount and direction of the error. The corks should be brought together rather gently, so as not to betray the character of the error to the operator, but the motions of the arms by which they are brought up nearly to contact should be free and sweeping. The error will probably be found rather constant in direction until the operator learns to correct it. Try bringing the corks together above the head, and also in asymmetrical positions.

b. Let the subject seat himself at a table with the millimeter scale before him. Set a pin in the middle of the scale, and bring the pin into the median plane of the subject and make the scale parallel to his frontal plane. Let the subject place his forefingers on either side of the pin, and, with closed eyes, try to measure off equal distances by moving both simultaneously outward along the scale. Note the result in millimeters; for this it may be convenient to mark the middle point of the finger-nails with an ink-line. A constant excess in the motion of one hand or the other will often be found. It is important that the subject should not open his eyes till his fingers are removed from the scale; for he will find it difficult not to correct his error if he knows its nature. The finger-tips should rest lightly on the scale, and the motions should be made from the shoulder by a single impulse; if they are too slow, and the subject attends to his sensations of position, the errors will be small and uncertain. The left hand, it is said, generally makes the greater excursion in right-handed persons not mechanics.

c. Repeat the tests, having the motions of the hands made

successively instead of simultaneously. The constant difference between the hands will probably not appear.

d. Let the subject start with his right and left hand each 20 cm. toward its own side of the median plane, and try to measure off equal distances on either side of those points, moving both hands at once in the same direction. Distances inward will be made too large, distances outward too small. In all these experiments with closed eyes we seem inclined to judge distance rather from the intention of equal motion and the continuance of motor sensations for equal times, than from the actual peripheral sensations.

The judgments of symmetry of position and motion rest upon very complex combinations of the dermal and kinæsthetic sensations, already made the subject of experiment above. As a result of this complexity the experiments of this group will be found to give rather variable results, from one subject to another, and in the same subject at different times.

Hall and Hartwell; Loeb; Delabarre; Bloch.

RECOGNITION OF THE POSITION OF THE BODY AS A WHOLE.

45. Recognition of Direction. In this experiment it is especially desirable that the subject should know as little as possible of the purpose of the experiment. Cause him to stand erect with his back against a wall. Choose a point on the opposite wall about the height of his shoulders. Let him look at it, and then require him, having closed his eyes, to point to it as exactly as possible with a light rod held symmetrically in both hands. Cause him also to hold the rod vertically and horizontally in the median plane; also horizontally parallel to the frontal plane. All these he will probably be able to do with much accuracy; or if, as sometimes happens, he shows a "personal equation," his error will be constant.

a. Cause the subject to repeat the experiment, this time turning his head as far as possible to the left after closing his eyes, taking pains to keep his shoulders square. Repeat, causing the subject to turn to the right. In both cases an error will be observed, the subject pointing too far in a direction opposite to that of the turning of the head. The subject will be able to hold the rod vertically, or horizontally, without error. Cause the subject to hold the rod in what he thinks is a horizontal position, in the median plane when his head is thrown well back; when bowed well forward. Illusions like those observed above, affecting directions in the plane of movement of the head, will result. Cause the subject to hold the rod in what he thinks is a horizontal position, parallel to the frontal plane, when his head is bowed to the right; when bowed to the left. Illusions similar to those in the previous experiments will appear. In all these cases judgment of one cardinal direction in space alone is affected; the other two show little or no errors.

b. Repeat the first part of experiment *a*; but instead of having the subject point to the designated object, have him walk toward it, keeping his shoulders square, his eyes shut, and his head turned to one side. He will walk more and more too far toward the side away from which his head is turned.

c. The illusion is due, at least in the case of turning the head about a vertical axis, to the position of the eyes; the eyes turn farther than the head in the direction in which it is turned, as may easily be observed upon any other person. From the eyes we judge the position of the head, and thus overjudging it, point too far in a contrary direction in trying to point to the required object (Delage). The illusions can be produced by motion of the eyes alone. Holding the head erect, and taking pains not to move it when moving the eyes, turn the closed eyes as far as possible to the right

or left, and then try to point to some determined object. An error like that in *a* will be observed. Turning of the eyes upward or downward has a doubtful result. Instead of closing the eyes, they may be kept open if an opaque screen is held close before the face. Repeat *a*, voluntarily turning the eyes as far as possible in the direction opposite to that of the turning of the head. The original error will probably disappear, or be found to have changed its sign.

For this illusion another eye explanation is suggested by Breuer, namely, that in such extreme turnings of the eyes, their actual position does not correspond with the intended position, but comes short of it. We infer the direction, however, from the intended position, and thus fall into the error in pointing. For the illusion in other positions of the head and even for this, his own preferred explanation is again different, and is partly based on the following experiment.

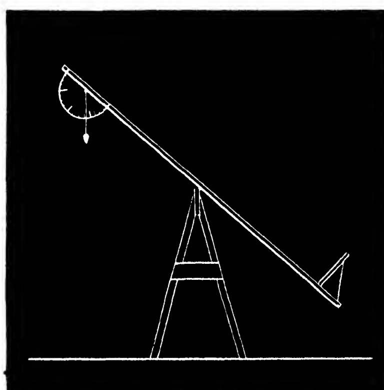
d. Close the eyes, and touch the tip of the nose or the forehead with a pin or a pencil while the head is in the usual position, and after a little try to touch the same spot again. The error, if any, will be very small. Repeat the touch in the normal position, and then turn the head to the right or left or incline it toward the shoulder or forward or backward. After holding it in the chosen position for half a minute, attempt to touch the spot again. Gross errors will result till corrected by practice. The error is one of underestimation, and should by itself alone produce a result directly the reverse of that found by Delage. Breuer, however, introduces another factor. His explanation for the inclined positions of the head is somewhat as follows: by means of the otolith-apparatus of the ear, we get a true perception of the amount of inclination of the head, at the same time that we get the erroneous perception just mentioned. The only way in which we can harmonize the

conflicting perceptions is by altering our judgment of the vertical, and with that, of course, of the horizontal. For the movements of rotation about a vertical axis the semi-circular canals (See Exs. 47–49) would furnish the knowledge of the true amount of turning, and from a similar combination of the true and false the illusions in that case would result.

This group of experiments, except perhaps the last, when tried under the ordinary conditions of the practice laboratory, seems liable to considerable individual variation; but sufficient care, especially as to the position of the eyes in turning to the right and left, should lead to a tolerable degree of success.

Aubert (Delage), 17 ff.; Loeb, *B*, 20 f., 31 f.; Breuer, 270 ff.

46. Vertical and Horizontal Positions of the Body. Secure the subject properly upon the tilt-board, and have him close his eyes. Start with the board vertical (head up). Require the subject to describe his position. He will probably announce that he is then leaning forward slightly. As a matter of fact he is, if his heels are against the board. Turn him slowly backward, and require him to say when he seems to himself vertical (head up), when he seems tilted backward at an angle of 45° from the vertical, when at an angle of 60°, when at 90°, when at 180°. Two classes of illusions will be found: angles of less than 40° will probably seem too small; those from 40° to 60° will be rightly



judged; those beyond 60° will seem too large. The subject will say that he is vertical, head downward, when he is yet 30–60° from it. The subject may be allowed a pillow if he desires it.

The illusions depend in large measure on the distribution of pressure on the soles and other surfaces of the body and the direction of pressure of the movable viscera and the blood.

Aubert (Delage), 40 ff.; Breuer, 270 f.

Sensations of Rotation.

47. Perception of Uniform Rotations. Let the subject be seated upon the rotation table with closed eyes, blindfolded if necessary. Turn the table slowly and evenly in one direction or the other. The subject will immediately recognize the direction and approximately the amount of rotation when the rate is as slow as 2° per second, or even slower. After continued rotation at a regular rate the sensation becomes much less exact or entirely fails. This fact has been generalized by Mach in the law that only change of rate, not continuous rotation, is perceived. After some pauses and short movements in one direction and the other, the subject may become quite lost, and give a totally wrong judgment of the direction of motion, if it is slow.

48. Illusion of Backward Rotation. Let the subject be seated as before. Rotate him a little more rapidly for half a turn, and then stop him suddenly. A distinct sensation of rotation in the opposite direction will result. Repeat, and when the illusory rotation begins, open the eyes. It immediately ceases. Close the eyes again, and, if strong, it again returns.

49. Location of the Organs for the Perception of Rotation. *a.* Repeat the first part of Ex. 48, letting the subject

give the word for stopping. At the same instant let him incline his head suddenly backward or forward, or lay it upon one shoulder or the other. The axis of rotation of the body will appear to change in a direction opposite to that of the inclination of the head; i.e., if the head is inclined to the right, the axis seems to incline to the left. The feeling is as if the body were rotating in the surface of a cone in a direction contrary to that of the first rotation. The head dictates the apparent axis of rotation. The same illusion occurs if the head is inclined during the actual rotation and straightened at the word for stopping. Turning the head to the right or left introduces no such illusion, because it does not change the axis of rotation of the head. The illusion comes out with very disagreeable strength when the rotation is rapid, and the subject changes the position of his head during the rotation.

b. Let the subject lie upon his side, and rotate him rather rapidly till the sensation of rotation becomes faint or disappears. Then let him turn suddenly upon his back or upon his other side. Turning upon his back starts rotation about a new axis, and it is felt in its true sense, while the rotation about the previous axis is felt as an illusion in its reverse sense. The resulting perception combines both. Turning completely over reverses the direction of motion completely, and the combined sensation and illusion produce a correspondingly powerful effect.

The change of the apparent axis of rotation with the change of position of the head points to the location in the head of the organ for such sensations. For the experiments by which the semicircular canals are indicated as this organ, and the arguments pro and con, see the literature cited by Aubert, Ayres, and others.

On the last three experiments, see: Aubert (Delage), 49 ff.; Brown; Mach; Wundt, 3te Aufl., I., 211 f.; II., 24,139.

50. Another Illusion of Rotation (Purkinje's dizziness) is due to involuntary motions of the eyes. Let the subject whirl rapidly on his heels with his eyes open till he begins to be dizzy. At first objects about him seem at rest, then to be turning in the opposite direction. Let him now stop and look at an even surfaced wall while the experimenter carefully observes his eyes, picking out some clearly marked fleck or spot as a point of observation. To the subject the surrounding objects will seem to continue to move in the same direction as before; i.e., in a direction contrary to his previous rotation; the experimenter will see the subject's eyes executing slow motions in one direction (in the direction of the original motion of the subject) alternating with rapid motions in the other. The subject himself may be able to perceive a corresponding irregularity of motion in the spots upon the wall at which he looks. He can easily observe the motions of his own eyes if he looks fixedly for twenty or thirty seconds at a flame or a strip of white paper in a bright light before beginning his rotation; the after-image (see Chapter V.) thus produced remains fixed on the retina, and its apparent movements betray the motions of the eye. If the eyes are closed after the rotation, the image will seem to move in one direction, and rather slowly. The illusion rests upon the subject's unconsciousness of the slow motions of his eyes. It is probable that these eye motions and the sensations of attempted restoration of equilibrium in other parts of the body are reflexly caused by the disturbance in the semicircular canals.

It should be noticed that this illusion is the exact reverse of that found with closed eyes in Ex. 48. There the subject feels a rotation of his own body contrary to that it previously received. If he was turned at first in the direction of the hands of a watch, on being stopped he would seem to be turning in a direction contrary to the hands. If these

motions were transferred to objects about him, they would, during the rotation, seem to move contrary to the hands, and after stopping, in the direction of the hands. In the Purkinje experiment the motion of objects is not thus reversed.

Those who try these rotational experiments should do so with caution, for the unpleasant effects of them sometimes last several hours.

Aubert (Delage), 52, 100 ff.; Mach. Aubert reprints Purkinje's paper on dizziness as an appendix to the translation of Delage.

Sensations of Progressive Motion.

51. Progressive motions, so far as they do not involve rotation, probably give us combinations of sensations from several different sources. The principle holds for progressive motions as for rotations, that we perceive changes of rate of motion, and not uniform motion; as long as the motion remains uniform we can by an effort of imagination conceive ourselves to be moving in either direction or to be standing still, except for what jarring there may be. The apparatus for the study of these phenomena will be found in railroad trains and elevators. See also Mach for special laboratory apparatus.

Aubert (Delage), 75 ff.; Mach; Brown; Breuer, 283.

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CHAPTER III.

Sensations of Taste and Smell.

THESE sensations are of secondary importance in psychology, and have received a correspondingly small share of investigation. In subjective quality they seem to stand midway between the general senses mentioned at the end of Chapter I. and the higher senses of Hearing and Vision.

SENSATIONS OF TASTE.

52. Tastes and Smells. Much of what is commonly called taste is really a combination of taste with smell and with touch in its various forms. With the nostrils held, try to distinguish by taste alone between small quantities of water and a weak solution of essence of clove in water. A discrimination that is easily possible with the nostrils open is difficult or impossible with the nostrils closed. The solution should not be swallowed, for then the olfactory region may be reached from the back of the nose.

53. Distribution of the Organs of Taste. *a.* Using the weaker taste solutions, and operating upon yourself with a mirror or on another person, find out as nearly as you can in what part of the tongue the strongest sensations are produced by each. Test the tip, the sides, the back, and the middle, putting the solutions on with a camel's-hair brush, and rinsing the mouth as often as necessary. Try also the hard and soft palates.

b. Dry the tongue with a handkerchief, and test the individual fungiform papillæ with the stronger solutions,

applying them with fine camel's-hair pencils. It will be found possible to get taste sensations from the single papillæ, though perhaps not all four from each. Rinse the mouth as needed. Test the surface of the tongue between the papillæ and observe that no taste sensations follow.

a. Rittmeyer; *b.* Oehrwall.

54. Minimal Tastes. *a.* Find what is the greatest dilution of the weaker solutions in which the characteristic tastes can still be recognized. The same quantity, e.g., half a teaspoonful, should be taken into the mouth at each trial, and may be swallowed with advantage. Rinse the mouth thoroughly as required. The following are the average proportions found by Bailey and Nichols for male observers: Quinine, 1:390 000; Sugar, 1:199; Salt, 1:2240; for Sulphuric Acid, which they used instead of Tartaric, the proportion was 1:2080.

b. The intensity of the sensation and the greatest dilution still tastable depend on the number of taste organs stimulated. Take a portion of one of the solutions of just tastable strength, found in *a*, add an equal quantity of water, and take a large mouthful of the mixture. The characteristic taste will still be perceived, perhaps more strongly than before.

a. Bailey and Nichols, *A*; Lombroso und Ottolenghi; Camerer, *A*.
b. Camerer, *B*.

55. Discriminative Sensibility for Taste. For a rough determination, test with solutions of sugar, taking first a small quantity of the standard 20% solution, then an equal quantity (the equality is important) of one of the weaker solutions, or first one of the weaker and then the standard, until a solution is found that is just recognizably different from the standard. Make this determination several times. The excess of sugar in the standard solution over the

amount in the solution just observably weaker, set in a ratio to the total percentage of sugar in the standard, measures the sensibility. Some experimenters may be able to distinguish the 18% from the 20% solution; their sensibility would then be expressed by the ratio 2 : 20.

Keppler.

56. Electrical Stimulation. *a.* Using a constant current, from a single Grenet cell, for example, and two small zinc electrodes, one applied to the inner surface of the under lip and the other to the tongue, notice the sour taste at the positive pole and the alkaline at the negative.

Von Vintschgau, 181 ff.; Oehrwall; Hermann.

SENSATIONS OF SMELL.

57. Minimal Odors. The keenness of smell may be tested with dilute solutions of odorous substances or with the olfactometer.

a. Test with solutions. Pour small quantities of the solutions of oil of cloves into little wide-mouthed bottles, filling each to about the same height. Mark all in an inconspicuous manner. Set the bottles a foot apart on a table in a place where there is moderate circulation of air, in the order of the strength of their solutions, beginning with the water and following with the weakest solution and so on. Require the subject to smell of the bottles in succession without lifting them from the table, beginning with the water, and to indicate that in which he first recognizes a characteristic odor. If the solutions stand for any length of time where they are subject to evaporation, it will be safer to prepare fresh ones before undertaking a new test. Other precautions will suggest themselves, such as the use of similar bottles, and care in filling them that none of the solution is left clinging near the mouth.

b. Test with the olfactometer. Test the sides of the nose separately. Push the odor-tube on till its end is flush with that of the glass tube, insert the bent end of the latter into the nostril, and gradually lengthen the exposed surface of the odor-tube till its odor is just discernible. Note in millimeters the length exposed.

a. Bailey and Nichols, *B*; Lombroso und Ottolenghi; Savelieff; *b.* Zwaardemaker, *A* and *C*.

58. Discriminative Sensibility for Odors. Using the double olfactometer with both odor-tubes drawn out far enough to give an unmistakable odor, but not too strong a one, say both drawn out 5 cm., find how far one or the other must be drawn out (or pushed back) to make the odor which it gives just observably stronger (or weaker) than that of the other. The test should be made with the sides of the nose separately (there is frequently a difference in sensitiveness between the two sides, due to mechanical obstruction or other cause), unless for some reason a bilateral form of experiment is desirable. Try a number of times, in half the tests smelling the weaker before the stronger, and in half the stronger before the weaker, but be careful to avoid fatigue.

59. Fatigue of Smell. *a.* Hold a piece of camphor gum to the nose, and smell of it continuously, breathing in through the nose and out through the mouth, for five or ten minutes. A very marked decrease in the intensity of the sensation will be observed, reaching perhaps even to complete loss of the odor.

b. It is important, however, to observe that fatigue for one substance does not cause obtuseness for all other substances, though it does for some. Smell of some essence of cloves and of some yellow wax, then fatigue for camphor as in *a*, and smell of the essence of cloves and of the wax again.

The odor of the wax will probably be fainter, that of the essence of cloves unaffected.

Aronsohn.

60. Combination of Odors. Experiment with the olfactometer on one side of the nose as follows. Hold against the end of the rubber odor-tube another odor-tube of wax (partly covered on the inside by a glass tube of the same size as that used in the olfactometer), in such a way that the air must pass through both to reach the nose. Then gradually increase the length of the rubber tube exposed till the odor of the wax is no longer perceived. If the experiment is carefully performed, a point may be found where the odors nearly balance. If the rubber is lengthened beyond this point, its odor overpowers that of the wax; if it is shortened, it is overpowered by that of the wax. A mixture of the odors in which both can be detected is difficult to find. Care should of course be taken to avoid fatigue.

A similar balance of odors was found by Zwaardemaker when the double olfactometer was used and the two sides of the nose received separate stimuli.

Zwaardemaker, *B*.

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CHAPTER IV.

Sensations of Hearing.

In these experiments a little knowledge of the physics of sound is presupposed — as much as would be given in an elementary course in physics. A very little knowledge of musical notation is also required, but hardly more than everybody has. No special musical skill is needed except in Exs. 70 and 93 *b*. It is also the author's belief that most persons calling themselves "unmusical," however truly they may rate themselves as performers, are very much in error as to their ability to discriminate musical sounds. The greatest difficulty in some of these experiments will be found in the continuous intrusion of outside sounds, and some even may have to be tried at night.

Sounds in General.

61. Minimal Sounds. *a.* Experiment in a large room as free as possible from noise. Let the subject be seated with his side toward the experimenter, his eyes closed, and his ear upon the other side plugged with cotton. Let the experimenter then find what is the greatest distance at which the subject can still hear the tick of a watch held at the level of his ear and on the prolongation of the line joining the two ears. This is easily done with sufficient accuracy by drawing a chalk line on the floor, marking off feet or meters and fractions upon it, and estimating by eye the point of the line directly under the watch. Try several times for each ear, both when the watch is being brought

toward the ear and when it is being carried away. The experimenter should from time to time cover the watch with his hand to discover whether or not the subject really hears, or is under illusion. For normal ears the distance found may vary from 2.5 m. to 4.5 m., and may even rise to as much as 9 m.

b. The subject should notice in this experiment the very marked intermittences of the sound when just upon the limit of audibility. It will for a few seconds be heard distinctly, and a few seconds later will as distinctly not be heard.

c. Faint sounds are apt to be underestimated. Place a sounding tuning-fork on the head and let the sound die away to almost complete extinction; then remove it. The drop to complete silence will often seem larger than the apparent intensity of the tone would justify.

On *a*, von Bezold, *A*; on *b*, Urbantschitsch, *A*; Lange; Münsterberg, *A*; on *c*, Stumpf, I., 388, who quotes from Fechner.

62. Discriminative Sensibility for Intensity of Sounds. Exact experiments on this topic are difficult to make, because of the very great difficulty of determining objectively the intensity of the sounds used. A rough determination can easily be made, however, with the sound pendulum (see chapter on apparatus). Choose a medium sound as a standard, and by the Method of Just Observable Difference explained under Ex. 24, find a sound that is just recognizably different from it. The discriminative sensibility is very much finer, apparently, when the question is not one of recognizing a difference, but of locating a sound as right or left of the median plane. Cf. Ex. 101 and Rayleigh.

Wundt, 3te Aufl., I., 364 ff.; 4te Aufl., I., 360 ff.; Stumpf, I., 345 ff.

63. Auditory Fatigue. *a.* Cause an assistant to strike once with a hammer on the floor, or to clap his hands.

With the ears open a single sound, or at most a single sound and transient echoes are heard. If, however, the ears are kept closed with the fingers till half a second or more after the stroke (the time may easily be fixed by rapid counting), the fainter echoes will be heard on the opening of the ears, like a new stroke. In the first case, fatigue from the original sound deadens the ears to the fainter echoes, though they may still be heard by attentive listening; in the second case they are more strongly heard because the closed ears are unfatigued. The sound produced by the simple opening of the ears without any objective stroke will be less if the finger is not put into the ears, but presses the *tragus* back upon the opening.

b. Strike a tuning-fork, press the stem firmly upon the mastoid process, or the crown of the head, and hold it there till the tone is no longer heard. Then instantly remove it, and after a second or two replace it upon the same spot, taking pains to press no harder than before. The fork will be heard again sounding faintly. The experiment may not succeed at first, but a few trials should not fail to show the effect.

c. Insert in the openings of the ears the ends of a rubber tube. Strike a tuning-fork and set it upon the tube at such a point that it sounds equally intense to the two ears. The sound will then probably appear to be located in the head midway between the ears — at least not nearer one than the other. After a few seconds strike the tuning-fork again, pinch the tube on one side, say the left, so as to shut off the sound from the ear on that side, set the tuning-fork at the proper place on the tube and keep it there till the sound has become rather faint. Then allow the pinched tube to open, and notice that the sound is now stronger on the left than the right and apparently located on the left. Try the experiment in reverse form, pinching the tube on the right.

Cf. later experiments on the analysis of compound tones by the fatigue method, Ex. 89 *c*.

Stumpf, I., 360–363. On *a*, Mach; on *b*, Corradi; on *c*, Urbantschitsch, *B*.

64. Inertia of the Auditory Apparatus. *a*. Inertia tending to keep the auditory apparatus out of function can be demonstrated as follows. Place the ends of a rubber tube in the ears, and set upon the middle of it a low tuning-fork sounding as faintly as possible. Notice that the sound does not reach its maximum intensity for an appreciable length of time; if the fork is barely audible, this may be as much as a second or two. Be careful not to increase the pressure of the fork upon the tube after first setting it on, for that will produce an objective strengthening of the tone; and allow an interval of several seconds between the tests so that the auditory apparatus may again come completely to rest. A tuning-fork that will preserve these minimal vibrations for some seconds, and complete freedom from distracting noises, will be found necessary for success.

b. Inertia tending to keep the auditory apparatus in function (positive auditory after-images) can be demonstrated as follows. Fasten upon the front of a rather solid pendulum a small tuning-fork, so that it shall project forward at right angles to the pendulum bar and the tines of the fork shall be vertically one above the other. On the three arms of a Y-tube attach three pieces of small rubber tubing, say quarter inch outside measurement. Those fitting on the upper arms of the Y should be of the same length, that fitting upon the stem may be of any convenient length. Insert the free end of the last mentioned tube in the outer passage of the ear, and hold the tips of the other tubes about half an inch apart, open end upward, in such a way that the tip of the tuning-fork, as the pendulum swings, will pass close over them. Strike the fork with a small rubber hammer as the

pendulum swings and notice the sound produced by the fork as it passes the ends of the tube. If a single continuous sound is heard, separate the tubes a little; if a double sound is heard, bring them together; and thus by shifting them back and forth find the place where the sounds just fuse into one. The auditory disturbance occasioned by the first pulse of sound outlasts the interval between the two, and blends with the second. Move the pendulum slowly over the end of one tube and then of the other, meantime pinching the tube over which the fork is sounding, to convince yourself that the tone is not heard at substantially the same instant in both tubes. It is possible from the rate of the pendulum and the separation of the tubes to find approximately the length of time through which the sensation persists.

c. Sometimes it is possible to get more lasting after-images and even those that are recurrent. Try with a tuning-fork struck and held a few seconds before one ear. Stop the fork by touching it, without removing it from the ear. The after-image is not very easy to observe; the lowest degree of it seems to be the transforming of faint outer noises into something qualitatively like the tone heard, or perhaps a selection of certain of those noises. The usual interval between the stimulus and the after-image is under fifteen seconds. The number of recurrences of the after-image differs in different subjects; for Stumpf, they seem to come by preference in the unstimulated ear.

Stumpf, I., 211 ff, 278; Urbantschitsch, *C.* For methods of demonstration permitting more accurate measurement of the persistence of tone, see Urbantschitsch, *C*, and Mayer, *A*.

65. Noise. Whether or not there is a distinctive sensation of noise different from that of a mass of short, dissonant, and irregularly changing tones, is yet under debate. A little attention to the noises constantly occurring, espe-

cially to their pitch, will easily convince the observer that a tonal element is present. This is striking when resonators (cf. notes on apparatus for simultaneous tones) are used, for they pick out and prolong somewhat the tones to which they correspond, but they are not indispensable. On the other hand, attention to musical tones will often discover the presence of accompanying noises.

Wundt, 3te Aufl., I., 420; 4te Aufl., I., 447 f; Stumpf, II., 497–515; Brücke; Exner; Mach, *B*, 117.

66. Silence. When circumstances promise absence of external sounds, notice that many are still present and distinct, though faintly heard. Notice also the pitch and changing character of the subjective sounds to be heard. Our nearest approach to the experience of absolute stillness is this mass of faint inner and outer sensations.

Preyer, *A*, 67–72; Stumpf, I., 380 ff.

SINGLE AND SUCCESSIVE TONES.

67. Highest Tones. With the apparatus at hand for the purpose, find what is the highest audible tone; i. e., if the cylinders are used, the shortest cylinder which still gives a ringing sound when struck with the hammer, or if the whistle is used, the closest position of the plunger at which a tone can still be heard beside the rush of air. If a number of persons are tested, it is not improbable that some will yet hear the tone after it has become inaudible for the rest.

Same references as Ex. 68

68. Lowest Tones. If low-pitched tuning-forks or other vibrators are at hand, find what is the slowest rate of vibration that can yet be perceived as a tone. In some physiological laboratories electric tuning-forks or interrupters may be found that have vibration rates of twenty-five per second. Low tones can be heard from these, though they have many

overtones. The latter can be partly damped by touching the tines midway of their length with the finger, and partly avoided by bringing the ear not to the free end, but to a point somewhat nearer the handle. The determination of the lower limit of audible pitch is difficult and uncertain because of the great difficulty which observers, even those of trained ear, find in distinguishing these lowest tones from the next higher octaves. The general character of these deep tones can be demonstrated with sufficient clearness upon the contra octave (C_1–C) of a church organ, if one is accessible and tuning-forks are lacking.

Von Bezold, *B*; Wundt, 3te Aufl., I., 423; 4te Aufl., I., 450; Preyer, *A* and *D*; Stumpf, I., 263, II., 551.

69. Some Characteristics of High and Low Tones.

a. High tones are smoother than low tones. This is clear with almost all tones used in music, and particularly so with those of reed instruments. The roughness of low tones is largely due to the beating of their partials among themselves (see Exs. 86 ff. and 79 ff.) and even with the fundamental tones; the high tones having fewer audible partials are freer from it. Play the scale of any instrument from its lowest to its highest tone, or sing the ascending scale. The difference of roughness is observable also with simple tones, but only at lower pitches, and is even there less marked.

b. In spite of the generally accepted fact that high tones produce a more intense sensation than low tones of equal physical energy, high tones are more readily suppressed by stronger lower tones than *vice versa*. Place an ordinary clock at a distance of a few feet and hold close before the ear a watch. When the watch is near the ear all the ticks will be heard. As it is gradually removed, a position can be found where the watch-tick that coincides with the clock-tick will be suppressed. When both make an equal number

of ticks to a second, and one gains a little on the other, there will occur periods in which no watch-ticks are heard, and, alternating with them, periods in which all are heard. If the watch beats oftener than the clock and both run at the same rate, a single watch-tick will be lost at regular intervals. When the clock is removed, all the ticks of the watch can easily be heard at the distance used. The phenomenon can be observed when the watch is on the opposite side of the head from the clock. To demonstrate weakness of high tones in suppressing lower tones, sound together a large and a small tuning-fork on their resonance cases, e. g., *c* and *c''*, *a''*, or *b''*, sounding the first very faintly and the second as loudly as possible. The first will still be heard even when the second is brought close to the ear. In this connection compare the difficulty of analyzing the compound tones in Exs. 86 ff., also Exs. 83 *b* and 84.

c. Some high tones are particularly strengthened by the resonance of the outer passage of the ear. These generally lie between c^4 and c^5, and give to the tones of this octave a superior strength and ear-piercing quality. They may be demonstrated easily with a small piston whistle. Find by adjustment of the piston the point at which the tone is most piercing. Insert in the outer ends of the ear-passages bits of rubber tubing half an inch long (which will change the resonance of the passages, making them responsive to a lower tone) and sound the whistle again. The piercing quality will be gone and the tone appear decidedly weaker. Remove the bits of tubing and sound the whistle as before; the original quality and intensity reappear.

d. Very closely associated with the pure tonal sensations are certain of a spatial quality. Compare in this respect the sensations of the tones observed in *c* above; or, better still, those of Ex. 67 with those of Ex. 68, or any other deep tones. Play the scale through the complete compass of any instrument, keeping this quality in mind.

e. Under certain conditions, low tones seem to be located in the head, high tones outside of it. Close the ears with the fingers and have an assistant strike a low tuning-fork (e.g., 50 vibrations per sec.), and set the stem of it upon the crown of the head; notice the location. Try the same with a high fork.

f. The emotional shading of tones changes with their pitch. Recall the descriptive terms used: Deep, low, bright, sharp, acute. Play the scale, and judge of the appropriateness of these terms to match the shades of feeling that mark the tones of low, middle, and high pitch, distinguishing those that refer to pitch from those enumerated in Ex. 90, which refer to timbre.

Stumpf, I., 202–220, II., 56–59, 227; also Mach, *B*, 120 ff. On *b*, Mayer, *B*; on *c* and *f*, Helmholtz, 116, 179, and 69 ff.; on *d*, James, II., 134 ff.; on *e*, Kessel.

70. Recognition of Absolute Pitch. *a.* This experiment gives accurate results only with those of very decided musical skill, but it may be tried with any subject that knows the names of the notes. Strike various notes in different parts of the scale of the instrument and require the subject to name the note given. Record the note struck and the subject's answer. He should be seated with his back toward the experimenter, or should keep his eyes closed.

b. Pitch differences in the perceptions of the two ears. The same tone, heard first with one ear and then with the other, seems to many observers, even professional musicians, somewhat different in pitch. Take two small rubber tubes of equal size and length (e. g., quarter inch tubes, two feet long), place an end of one in the right ear, an end of the other in the left, and bring the free ends near together on the table. Then have an assistant strike a tuning-fork and

present it alternately to the ends of the tubes. The difference between the two ears is said to vary more or less from day to day and to be different in amount for tones of different pitch. Such differences may be observed by the unmusical.

Stumpf, I., 305–313, also II., index, *Höhenurteile*, for experiments on trained musicians; von Kries, *B*; on *b*, Stumpf, II., 319 f.

71. Just Observable Difference in Pitch. Test as follows with the set of mistuned forks. Let the subject pick out from the mistuned forks that which sounds to him just noticeably different from the normal fork, striking and holding them successively (never simultaneously) over a resonance bottle. If all of them seem more than just observably different, let him put the riders on the one that is next higher, and gradually lower the pitch by sliding them toward the ends of the fork till the two forks, heard successively, are just different and no more. The experimenter may then determine the error of the subject in vibrations per second approximately by counting the number of beats produced by the forks when sounded together. If the number of beats per second is less than 2 or more than 6, it will be best to get the difference in pitch with some other of the forks first, so as to avoid too slow or too rapid counting, and from that to arrive at the difference from the standard fork. Repeat the test several times, sometimes sounding the standard fork first, and sometimes that to be compared with it, and average the result. Take care to avoid fatigue. This experiment will not be refined enough for testing those of keen musical ear.

Preyer, *A*, 26 ff., *D*, 64; Stumpf, I., 296–305; Luft.

72. Differences in Pitch that are Just Recognizable as Higher or Lower. It is easier to recognize a difference than to tell its direction. Experiment as in Ex. 71, but

require the subject this time to pick out and adjust a fork that is just observably sharper or flatter than the standard.

Preyer, *A*, 28, 36. For experiments on extremely unmusical subjects, see Stumpf, I., 313-335.

73. Number of Vibrations Necessary to Produce a Sensation of Pitch. Arrange an apparatus for blowing soap-bubbles with a mixture of hydrogen and air. Blow bubbles of different sizes and touch them off with a match, either in the air, or (if proper precaution is taken to prevent the ignition of the mixed gases in the vessel and any resonance in the pipe), while still hanging. The explosion of these bubbles is supposed to produce a single sound wave. The pitch of the sounds produced cannot be accurately given, but the report of the large bubbles is distinctly deeper than that of the small ones.

Brücke; Cross and Maltby; Herroun and Yeo.

74. The Apparent Pitch of Tones is Affected by their Quality. Tones of dull and soft character seem lower in pitch than those that are brighter and more incisive. Require the subject to pick out on some stringed or reed instrument the tone corresponding to that produced by blowing across the mouth of a medium-sized bottle. Too low a note at first will generally be chosen, at least by those without special musical training. The tones should be sounded successively, not at the same time, during the test. Afterward they may be sounded together, and the pitch of the bottle determined approximately by finding with which tone of the instrument its tone makes the slowest beats (cf. Ex. 79). It should be remembered, however, that it will be possible to get beats also with tones an octave lower and an octave higher than that corresponding most nearly with the true pitch of the bottle tone.

Stumpf, I., 227-247, especially, 235-245.

75. Recognition of Musical Intervals. Cause a familiar air to be played, first in the octave of c and then in that of c'' in the same or another key. Even those of no musical training will easily recognize that the air (i. e., the succession of musical intervals in fixed rhythmical relations), is the same in both cases; and any mistake or variation will be noticed as easily as if the air had been repeated at the first pitch. With the unmusical, however, the recognition is often rather of the rhythm than the intervals; try therefore a repetition of the air changing some of the intervals but preserving the original rhythm. The power of recognizing intervals is very much more highly developed in persons of musical training, but any one that can whistle a tune at one pitch and repeat it recognizably at another undoubtedly has the rudiments of interval recognition.

For exact methods of testing the accuracy of the power of recognizing intervals, see Preyer, *A*, 38–64; and Schischmánow, and the references given by them.

76. Pitch Distances. Beside the interval relations of tones, and overshadowed by them in musicians, are certain relations of separateness or distinctness or distance in pitch, which do not depend on the ratios of vibration rates. Equal musical intervals (i.e., intervals between tones that have vibration rates in a fixed ratio to each other, e.g., C D and c'' d'') do not correspond to equal pitch distances. Sound the half-tone interval c *c-sharp* through the range of the instrument, beginning in the bass and ascending. Notice the increasing distinctness and separation of the tones as the interval is taken higher and higher. For the very highest tones there is probably a decrease of separateness again. The difference is most striking, however, with intervals smaller than those in common use, e.g., with quarter or eighth tones. On the harmonical (cf. notes on apparatus) strike in succession the *c-sharp* and d keys in the four lower

octaves, beginning with the lowest. In this instrument the *c-sharp* key is given to another *d*, a comma, or about one-ninth of a tone, flatter than the regular *d* of the scale.

Stumpf, I., 247–253; Lorenz, and the discussion between Wundt, Stumpf, and Engel; Helmholtz, 264–265; Münsterberg, *C*.

77. The Effect of a Given Tone in a Melody depends in part on the succession of tones in which it stands. Cause a simple air, in which the same tone recurs in different successions of tones, to be played, and notice the difference in effect in the different circumstances, or simply play the ascending and descending scales.

Mach, *B*, 130–131.

78. Tones that Vary Irregularly in time and in pitch are unpleasant. Test with a piston whistle.

Simultaneous Tones.

79. Beats. When tones that are different in pitch are sounded at the same time, they mutually interfere, and make the total sensation at one instant more intense and the next instant less intense. This regular variation in intensity is called "beating." Exs. 71 and 74, where beats have been used incidentally, are a sufficient introduction to them.

a. The rapidity of beats depends on the difference in the vibration rates of the beating tones. Prepare two bottle whistles of the same size, and blow both at the same time. Slow beats will probably be heard. If not, pour a little water into one bottle (thus raising the pitch of its tone), and blow as before. Continue adding water, a little at a time, till the beats lose themselves in the general roughness of the tone. Blow the bottles separately now and then to observe the increasing difference in pitch. The same may be shown with a couple of piston whistles, if they are first

adjusted to unison, and then the piston of one or the other is slowly pushed in or pulled out.

b. Tones that are a little more or a little less than an octave apart may give beats. Try with a pair of octave-forks on resonance boxes or held over resonance bottles, one of which has been slightly lowered in pitch by weighting the prongs with wax or a bit of rubber tubing. In this case the beating-tones are the tone of the lower fork and the difference tone (see Ex. 82). Repeat the experiment on a reed instrument. In this case beats may be heard between the higher tone and the first over-tone of the lower (see Ex. 86).

c. The rate at which the roughness of rapid beats disappears, as also the rate which produces the greatest roughness, differs with the pitch of the beating-tones. Sound the following pairs of tones which have somewhat near the same difference in vibration rates per sec., namely, 33; and observe that the roughness from the beats decreases and finally disappears entirely at about the fourth pair; *b′ c″*, *c′ d′*, *e g*, *c e*, *G c*, *C G*. The *a′* and *c″* tuning-forks give a vanish of roughness, representing a rate of 80–88 per sec.

Helmholtz, 159–173; Stumpf., II., 449–497, especially 461–465; Mayer, *A*; Cross and Goodwin.

80. Beats Betray the Presence of very Faint Tones, both because the total stimulus is actually stronger in the phase of increased intensity, and because intermittent stimuli are themselves more effective than continuous ones.

a. Strike a pair of beating tuning-forks, and hold one at such a distance from the ear that it is very faint or quite inaudible. Then bring the other fork gradually toward the ear, and notice the unmistakable beats.

b. Strike a tuning-fork and hold it at a distance, being careful to have the fork sidewise or edgewise, not corner-

ing, toward the ear. Rotate the fork one way and the other about its long axis, and observe the greater distinctness of the tone, due in this case simply to its intermittence.

81. Beats are in general Attributed to the Tone that Receives Attention; in the absence of other determining causes, to the louder tone, to the lower tone, or to the whole mass of an unanalyzed compound tone (see introduction to Ex. 86).

a. Set two properly tuned resonance bottles about a foot apart on the table. Strike two forks that beat, and hold them over the bottles. While both are about equally intense, it is easy, by mere direction of the attention, to make the beats shift from one to the other.

b. Turn one of the forks an eighth of a turn about its long axis, which will weaken its tone, and observe that the beats seem to come from the other fork. By turning first one fork and then the other, the location of the beats may again be made to shift at pleasure. If tuning-forks on resonance boxes are at hand they may be used, and the tone of one weakened by covering the opening of the box with a bit of cardboard.

c. Warm the c' fork in any convenient way (holding it clasped in the hand will do). This will flatten it somewhat. Strike it and the c'' fork, and press the stems of both on the table at the same time; or, better, on the sounding-board of the sonometer. Observe that the beats seem to come from the c' fork unless it is very faint.

d. Tune a string of the sonometer so that its third partial (or corresponding harmonic) beats slowly with the c'' fork. (On partials and harmonics cf. Exs. 86–89.) Strike the tuning-fork, and hold it over a resonance bottle, or press its stem against the table at arm's length from the string. Then pluck the string and attend to its tone; the beats may

seem to affect the whole compound tone of the string. But this will not happen if the tone of the string is analyzed, or if the attention is directed to the fork. The same may be tried on the piano by picking out from the mistuned c'' forks one that beats slowly with c'' on the piano. Strike the *f* key and hold it down; strike the fork, and observe the beats as before. Cf. Ex. 69 *a*.

Stumpf, II., 489–497.

82. Combination Tones: Difference Tones.[1] When two tones are loudly sounded at the same time they produce by their combination other tones, one of a pitch represented by the difference of the vibration rates of the two original or generating tones, and one of a pitch corresponding to their sum. The existence of the summation tones has been disputed, and they are hard to hear. The difference tones, however, are easy to hear, at least when they are considerably lower in pitch than the generators, when the latter are loud and sustained, and when they make a consonant interval — though the last is not essential. A loud difference tone may itself take the part of a generator and produce yet another difference tone — a difference tone of the second order — and so on, though difference tones of higher orders are heard with difficulty even by skilled observers. Difference tones are hard to hear on the piano and similar stringed instruments because of the rapid decline in the strength of the generators. The difference tones are sometimes called Tartini's tones, after an early observer of them.

a. Repeat Ex. 79 *a*, continuing to pour water into one of the bottles till the difference tone appears. At first the roughness of the beats and the difference tone may both be

[1] König distinguishes between "difference tones" and "beat tones." Both tones, however, generally have the same pitch, and the older term for them has here been retained; strictly speaking, however, the "difference tones" heard in these experiments are "beat tones."

heard at once. Try the same with the piston whistles, first setting them at unison, and then slowly pushing the piston of one in or out while blowing rather hard. The beats will almost immediately give place to a low difference tone which may be heard ascending through several octaves before becoming indistinguishable from the generators. The double warning whistles used by bicyclists give a fine difference tone, to which indeed they owe their deep and locomotive-like quality.

b. Difference tones are strong on reed instruments. Press the adjacent white keys of a parlor organ, or the harmonical, by twos, beginning at *c* and going up a couple of octaves. If there is difficulty in hearing the difference tone, sound the upper tone intermittently and listen for the difference tone at the instant of pressing the key.

c. Sound c'' and d'' which should give *C* as a difference tone (594—528=66). Sound also d'' and e'' which should give the same (660—594=66). If, however, the tuning is inexact, as it is intentionally in the tempered tuning of keyed instruments, these difference tones will be somewhat different and may be heard to beat with each other when c'', d'' and e'' are sounded at once. Notice that these beats are not heard when the tones are sounded in pairs. On the harmonical this difference may be brought about by sounding one of the tones flat by pressing its key only a little way down. The same thing may be shown with three piston whistles blown at once, by a little careful adjustment of the pistons.

d. In the case of reed instruments the difference tones probably owe part of their intensity to the vibrations of the air in the wind chest. When two whistles are blown by one person something of the same kind may happen. In order to make a clean experiment, have the whistles blown by two assistants, or observe the difference tones from tuning-forks.

e. The location of difference tones. The location of these tones is sometimes influenced by the location of their generators, but under favorable circumstances they seem to arise in the ears or even in the head. This is strikingly the case, both for the blower and the listeners, with the difference tones produced with the piston whistles. Cf. Ex. 69 *e.*

Helmholtz, 152–159; Stumpf, II., 243–257; König; Preyer, *C* and *D*; Hermann.

83. Blending of Tones. The degree to which tones blend with one another differs with the interval relation of the tones taken. It is, according to Stumpf, greatest with the octave, less with the fifth, less again with the fourth, slight with the thirds and sixths, and least of all with the remaining intervals.

a. Try on the instrument the extent to which the tones forming these intervals blend, also those forming intervals greater than the octave: double octave, twelfth, etc.

b. The blending in case of the octave is so complete under favorable circumstances as to escape the analysis of trained ears. Use two tuning-forks, one an octave higher than the other, on resonance cases or held over resonance bottles. Sound the forks, first the higher, then the lower. For a while the higher fork will be heard sounding in its proper tone, but by degrees it will become completely lost in the lower, and a subject with closed eyes will be unable to say whether or not it yet sounds. Cf. Ex. 69 *b.* Stop the lower fork, or remove it from its resonance bottle, and notice that the higher is still sounding. Notice the change in timbre (cf. Ex. 90) produced by the stopping of the higher fork — something like the change from the vowel O to the vowel U (oo).

On *a*, Stumpf, II., 127–218, especially 135–142; for his experiments on the unmusical confirming his grades of blending, 142–173. On *b*, Stumpf, II., 352–358, and Helmholtz, 60–61.

84. Analysis of Groups of Simultaneous Tones. Ease of analysis depends on a number of conditions, among others on the following.

a. Analysis is easier for tones far distant in the scale. Compare the ease of recognizing the sound of the c'' fork when c' and c'' are sounded together, with that of recognizing c''' when sounded with c'. Compare also the case of distinguishing c' and a' with that of distinguishing c' and a''.

b. Analysis is made easier by loudness in the tone to be separated. Repeat Ex. 83 *b*, sounding the c' faintly, the c'' strongly. Little difficulty will be found in keeping the latter distinct.

c. Analysis is easier when the tones make intervals with little tendency to blend. Compare the ease of analysis of '' c'' and c' a' or a' c''. Also notice that the addition of d'' (octave of d', fifth of g', fourth below g'') to the chord g d' g' g'' produces a less striking change than the addition of b' (major third of g', minor sixth below g'') to the same chord.

d. Analysis is easier with sustained than with short chords. Repeat the last experiment, making the chords very short, and notice that the difference made by inserting either d'' or b' is less marked. Cf. also Ex. 100.

Stumpf, II., 318–361; also his experiments, 362–382.

85. The Lower Tone of a Chord Fixes the Apparent Pitch of the Whole. *a.* Repeat Ex. 83 *b*, and notice that when the c' fork is stopped, the tone appears to jump upward an octave in pitch (i.e., it takes the pitch of the c'' still sounding); but when the c'' fork is removed, the quality of the tone is changed, but not its pitch.

b. Strike the chord C c'' e'' g'' or G e' g' c'', and compare the effect upon the pitch of the whole mass of tone produced by omitting C or G alone with that of omitting any one or all three of the higher tones. See also the function

of the lowest partial of a compound tone in fixing the pitch, noticed below.

Stumpf, II., 383-392.

86. Compound Tones. Almost all tones heard, and indeed all those used in music, are not simple tones, but compound. The tone given by the *C* string of a piano is made up of at least *C*, *c*, *g*, *c'*, *e'* and *g'*, and generally other tones. The lowest tone of the group gives the pitch attributed to the whole, and is known as the *fundamental*, the other tones as *over-tones*. In another way of naming them, the component tones are all *partial tones* or *partials*, the fundamental being called the *first* or *prime partial*, the next higher the *second partial* and so on. The *first* over-tone is thus the *second* partial tone, the *second* over-tone the *third* partial, and in general the same tone receives as a partial tone a number one higher than as an over-tone. The vibration rates of the partial tones of a compound are generally once, twice, three times, four times, the rate of the fundamental, and so on. In some cases, however, e.g., in bells and tuning-forks, one or more of the partial tones may have a vibration rate not represented in this series, and discordant with the fundamental tone. In what follows, the regular series of partial tones is meant except where the contrary is specified.

Partial Tones. If resonators are at hand, the demonstration of the partial tones will be easy. Sound on a stringed or reed instrument the tones to which the resonators are tuned, and notice that they resound strongly to these tones and less strongly or not at all to other tones adjacent in pitch. Then sound the tone to which the largest of the resonators is tuned (or a tone an octave lower), and try the resonators in succession. Notice that others also resound (at their own proper pitch), thus betraying the presence of the tones to which they are tuned, and

thus the composite character of the tone under examination. Which resonators will "speak" will depend on the instrument used; reed instruments give a long and perfect series, piano and stretched wires a perfect series generally as far as the ninth or tenth partial, and stopped organ-pipes a short series. If difficulty is found in knowing when the resonator is resounding, it will be found useful to apply it to the ear intermittently, alternating, for example, two seconds of application with two seconds of withdrawal.

87. Partial Tones: Analysis by indirect means. *a.* By sympathetic vibration. This succeeds especially well with the piano. Press the *c* key and hold it down so as to leave its strings free to vibrate; then strike the *C* key forcibly, and after one or two seconds release it. The *c* strings will be found to be sounding. Repeat, trying *c-sharp* or *b* instead of *c*; they will be found not to respond. Repeat the experiment, substituting *g*, *c'*, *e'*, *g'*, or *c''*; all will be found to respond but in lessening degrees. Other keys between *C* and *c''* may be tried but will be found in very faint vibration, if at all.

b. By beats. This will succeed best with a reed instrument, e. g., a parlor organ or the harmonical. By pressing the keys of the instrument only a little way down, any of its tones may be sounded a little flatter than its true pitch and so in condition to beat with any other tone having that true pitch. Sound at this flattened pitch the over-tones of *C* in succession while *C* is sounding, and notice the slow beats that result. For verification sound other tones not over-tones of *C*, and notice that the beats when present are much more rapid.

88. Partial Tones: Direct analysis without special apparatus. The directions given here apply to the sonometer, but will be readily adaptable to any stringed instrument in which

the strings can be exposed. It is easier to hear any partial tone in the compound, if the partial is first heard by itself, and then immediately in combination with the rest. On strings this is easily done by sounding the partials as "harmonics." Pluck the string near one end (say about one-seventh of the length of the string from the end), and immediately touch it in the middle with the finger or a camel's-hair brush. The fundamental will cease to sound and its octave (the second partial) will be left sounding, as a "harmonic." With it sound also other even-numbered partials, but less strongly. Pluck as before, and touch the string at one-third its length; the third partial will now sound out strongest, with the sixth, ninth, etc., more faintly. Thus by plucking the string and touching it respectively at one half, one third, one fourth, one fifth, one sixth, one seventh, one eighth, one ninth, and one tenth its length from the end, the series of tones corresponding to the 2d, 3d, 4th, 5th, 6th, 7th, 8th, 9th, and 10th partials can be heard, each in large measure by itself. In getting the higher "harmonies" it will be found better to pluck nearer the end than one seventh, and in no case should the string be plucked at the point at which it is presently to be touched. (Cf. Ex. 90 *b*.)

To hear the partial tones when sounding in the compound, proceed as follows. Sound the required tone as a "harmonic," and then keeping the attention fixed on that tone, stop the string and pluck it again, this time letting it vibrate freely. The tone just heard as a "harmonic" will now be heard sounding with the rest as a partial. When the partial is thus made out, verify the analysis by touching the string again and letting the tone sound once more as a "harmonic." Try in this way for the partials up to the tenth; first for the 3d, 5th, and 7th, afterward for the 6th, 4th, and the 2d, which is the most difficult of all. It is said that analysis

is easier at night (not alone on account of the greater stillness) and when one ear is used, and that certain positions of the head favor certain partials.

89. Partial Tones: Direct analysis without apparatus. Certain parts of a compound tone are sometimes so separated by their dissonance, intensity, or pitch that they stand out with striking clearness.

a. Strike a tuning-fork on a hard surface, and observe the high, ringing, dissonant partials. They fade out before the proper tone of the fork, and are heard best when the fork is not held near the ear.

b. As the tone of a string is allowed to die away of itself, different partial tones come successively into prominence. Try with a low piano string, keeping the key pressed down while the sound fades, or with the sonometer. Something of the same kind, but less marked, happens in the dying away of a low tone on a reed instrument when the air is allowed to run low in the bellows.

c. When a tone is sounded continuously for some time on a reed instrument with one of the keys clamped down, different partials come successively into prominence, either through varying fatigue or the wandering of attention.

Helmholtz, 36–65; Stumpf, II., 231–243; see also the index under *Obertöne*; Mach, *A*, 58, *B*, 127.

90. Timbre. The peculiar differences in quality of tones (distinct from pitch and intensity) which are known as differences in timbre (tone-color, clang-tint, *Klangfarbe*), are due largely to differences in the number, pitch, and intensity of the partial tones present. Compare in this respect the dull-sounding bottle-tones or the tones of tuning-forks held over resonance bottles, and the more brilliant tones of a reed or stringed instrument; the first are nearly simple tones, while the second have strong and numerous over-tones.

a. Notice the difference in quality between the tone given by a tuning-fork held before the ear and that given by the same fork when its stem is pressed upon the table. In the second position the over-tones are relatively stronger.

b. Notice the differences in quality in the tone of a string when it is plucked in the middle, at one third its length and at about one seventh. When plucked in the middle, many odd-numbered partials are present, and the even-numbered partials are either absent or extremely faint, and the tone is hollow and nasal; when plucked at one third, the third, sixth, and ninth partials are wanting, and the tone is hollow, but not so much so as before; when plucked at one seventh all the partials up to the seventh are present. For their theoretical intensities, cf. Helmholtz, 79.

c. Try also plucking very near one end, plucking with the finger-nail and striking the string with a hard body, e. g., the back of a knife-blade; all these bring out the higher and mutually discordant partials strongly, and produce a brassy timbre.

Helmholtz, 65–119; Stumpf, II., 514–549.

91. In Successive Chords the Whole Mass of Tone seems to move in the same direction as the part that changes most. Strike in succession the chords *e′ g′-sharp b′ e″*, *a a′ c″-sharp e″*, or *a c′ e′ c″*, *a c′ f′ c″*. If the attention is directed to the bass in the first example and to the alto in the second the whole mass of tone will appear to descend in the first case and to ascend in the second. If the attention is kept on the soprano part the illusion will not appear, as also when the observer examines his sensations critically. Cf. also Ex. 81 *d*, where beats of a partial tone are attributed to the whole compound tone.

Mach, *B*, 126–127; Stumpf, II., 393–395.

92. Simultaneous Tones interfere somewhat with one another in Intensity.

1*a*. 2. 2*a*. 3. 3*a*.

a. Play the groups of notes numbered 1, 2, and 3 and observe the slight increase in the apparent intensity of the remaining tones as one after another drops out, making 1 sound like 1a, 2 like 2a, and so on. On the piano it will be well to play the notes an octave or two lower than they are written.

4. 4*a*. 4*b*.

b. Play the notes marked 4, and notice that the increase of loudness seems to affect the note (highest or lowest) that receives particular attention, making the effect in one case like 4*a*, in the other like 4*b*.

Mach, *B*, 126; Stumpf, II., 418–423.

93. Consonant and Dissonant Intervals. *a*. The consonant intervals within the octave are the unison, octave, fifth, fourth, major sixth, major third, minor third, and minor sixth. They will be found to decrease in smoothness about in the order given. Try them beginning with the octave and at *c*, as follows: *c c′*, *c g*, *c f*, *c a*, *c e*, *c e-flat*, *c a-flat*. Try the last four intervals also in the octave of *c″* or *c‴* and notice that they are less rough than when taken in the

octave of *c*. Any other intervals within the octave are dissonant. Try *c c-sharp*, *c d*, *c b*, *c b-flat*, *c f-sharp*. The roughness is due to beating partial tones and in general is greater when these stand low in the partial tone series and are loud, and when they lie within a half-tone of each other. Work out for the tones of several of the intervals the series of partial tones up to the eighth. In general the extension of intervals into the second octave (taking the higher tone an octave higher or the lower tone an octave lower) does not change the fact of consonance or dissonance, though it may change the relative roughness.

b. Those fitted by musical training to pronounce upon questions of consonance and dissonance hold that dissonance can be perceived between simple tones under conditions that exclude beats, and that consonance is something more than the smooth flowing of tones undisturbed by beats. The test is easy to make. Hold tuning-forks making the interval to be tested one before each ear, and if there are beats, carry the forks far enough away in each direction to make the beats inaudible. Only those of musical ear, however, can pronounce upon the result.

Helmholtz, 179–197; Stumpf, II., 470, 460; Wundt, 3te Aufl., I., 439, II., 47 ff; Mach, *B*, 129–130; Preyer, *D*, 44 ff.

94. Consonant and Dissonant Chords. In order to form a consonant chord, all the intervals among the tones must also be consonant. The only chords of three tones which fulfil this condition within the octave are represented by the following: Major *c e g*, *c f a*, *c e-flat a-flat*, minor *c e-flat g*, *c f a-flat*, *c e a*. Try these and for comparison any other chord of three tones having *c* for its lowest tone.

Helmholtz, 211 ff.; Wundt, 3te Aufl., II., 61, 63 ff.

95. Major and Minor Chords. Compare the chords *c″ e″ g″* and *c″ e″-flat g″*. This unmistakable difference in effect

depends in part at least on the fact that in the major chord the difference tones of the first order are lower octaves of *c''* itself, while in the minor chord one difference tone is not such at all, and if taken in the same octave with the chord would be highly dissonant. For the major chord, when taken in the octave of *c''*, the difference tones are *c* and *c''*, for the minor chord *c* *c-flat*, *A-flat*. Try on a reed instrument the difference tones generated by *c'' e''*, *c'' g''*, *c'' e''-flat*, *e''-flat g''*, first separately; and then, while *c''* and *g''* are kept sounding strike *e''* and *e''-flat* alternately.

Helmholtz, 215–217; Stumpf, II., 335, 376 ff.; Wundt, 3te. Aufl., II., 61 ff., 67 ff.

96. Cadences. Modern music requires the prominence of the key note or tonic and of the chord in which it holds the chief place at the beginning of a piece of music and at the end. The feeling of the appropriateness of this close, and especially of the succession of chords in the cadences above, can hardly fail to appeal even to the unmusical.

Helmholtz, 293.

97. The Absolute Time Relations of music have much to do with its emotional effect. Have a familiar piece of music played in its proper time, then very slowly and very rapidly.

Binaural Audition and the Location of Sounds.

98. Unison Tones Heard with the Two Ears. *a.* Strike a pair of unison forks that will sound equally loud and vibrate an equal length of time, and hold one before each ear, three or four inches away; a single tone of rather indefinite location will be heard. As the forks are brought nearer, their tone seems to draw by degrees toward the median plane; and when they are very loud and near, the tone may seem to be in the head. Return the forks to their first position and then move one a little nearer or a little farther away, and notice that the sound moves to the side of the nearer fork. When the difference in distance has become considerable that fork alone will be heard.

b. Bring the forks again into the positions last mentioned—one near and one far, (or better, place one fork on a rubber tube one end of which has been inserted in the opening of the ear and hold the other fork before the other ear), and then with the free or more distant fork make slow rhythmical motions toward and away from the ear, or rotate the fork slowly about its long axis, attending meantime to the fork on the other side. Alternate variations in the intensity of the tone of this fork corresponding to the approach and recession of the other and apparently unheard fork can be observed.

c. Repeat *b* and notice that when the changes in intensity are considerable there is a simultaneous shifting of the place of the tone, towards the median plane when the tone grows stronger, and away when it grows fainter. These changes of place are, however, less marked than the changes in intensity and those accompanying slight changes in intensity generally escape observation.

Schaefer, *B*; Thompson; Urbantschitsch, *B*.

99. Beats Heard with Two Ears. *a.* Operate as in Ex. 98 *a*, with forks beating three or four times a second.

b. Try with a pair of very slow beating forks (once in two or three seconds). Notice a shifting of the sound from ear to ear corresponding to the rate of beating.

c. Try again with a pair of rapid beating forks (twenty or thirty a second), and notice that the beats are heard in both ears.

Schaefer, *A*, *B*, and *C*; Thompson; Cross and Goodwin.

100. Difference of Location Helps in the Analysis of Simultaneous Tones. Compare the ease with which the tones of a pair of octave forks are distinguished when the forks are held on opposite sides of the head with the difficulty of analysis in Ex. 83 *b*.

Stumpf, II., 336, 363.

101. Judgments of the Direction of Sounds. These depend in general on the relative intensity of the sounds reaching the two ears, but there is pretty good reason to believe that other factors co-operate and that tolerably correct judgments, both as to distance and direction, can sometimes be made from the sensations of one ear.

a. Let the subject be seated with closed eyes. Snap the telegraph snapper at different points in space a foot or two distant from his head, being very careful not to betray the place in any way, and require him to indicate the direction of the sound. Try points both in and out of the median plane. Observe that the subject seldom or never confuses right and left but often makes gross errors in other directions. Constant tendencies to certain locations are by no means uncommon.

b. Have the subject hold his hands against the sides of his head like another pair of ears, hollow backward, and try the effect upon his judgment of the direction of the snapper.

c. Find approximately how far the snapper must be moved vertically from the following points in order to make a just observable change in location: on a level with the ears in the median plane two feet in front; opposite one ear, same distance; in the median plane behind the head, same distance. Find the just observable horizontal displacements at the same points. A convenient way of measuring these distances is to clamp a yard-stick to a retort-stand, bring it into the line along which measurements are to be made and hold the snapper over the divisions of the stick. Snap once at the point of departure, then at a point a little way distant in the direction to be studied; again at the first point, so that the subject may keep it in mind, and then at a point a little more distant, and so on till a point is finally found which the subject recognizes as just observably different. Repeat, alternating snaps at the point of departure with those at a greater distance than that just found, decreasing the latter till a point is found where the directions can be no longer distinguished. Make a number of tests each way and take their average.

d. Continuous simple tones are very difficult to locate. Place a tuning-fork on its resonance case at some distance in front of the subject (seated with closed eyes), another at an equal distance behind him. With the help of an assistant strike both forks, and after a little have one of them stopped and the mouth of its resonance box covered. Require the subject to say which has been stopped. His errors will be very frequent. Compare with this his ability to distinguish whether a speaker is before or behind him.

On *a*, Preyer, *B*; von Kries, *A*; on *c*, Münsterberg, *B*; on *d*, Rayleigh.

102. Intercranial Location of Sounds. *a*. Sounds originating outside the head are not located in the head when heard with one ear. Hold a loud-sounding tuning-fork

near the ear, or place it on a rubber tube, one end of which is inserted in the opening of the ear, and notice that the sound when strong may be located in the ear, but does not penetrate farther. Insert the other end of the tube in the opening of the other ear and repeat. The tone, if loud, will appear to come from the inside of the head. Removing and replacing the fork several times will help to give definiteness to the location.

b. Repeat the experiment, but use a fork sounding as faintly as possible (e.g., set in vibration by blowing smartly against it), and notice that the location, when a single ear receives the sound, is not so clearly in the ear, and, when both receive it, not so clearly in the head, perhaps even outside of it. Cf. also Ex. 103 *b*. Both *a* and *b* may also be made with beating tones instead of a single one. See also Ex. 69 *e*.

Schaefer, *B*.

103. Location of the Tones of Tuning-forks Pressed against the Head. *a*. Strike a large and loud-sounding tuning-fork, and press its stem against the vertex. The tone will seem to come from the interior of the head, chiefly from the back. While the fork is in the same position, close one of the ears with the finger, not pressing it too tight; the sound will immediately seem to concentrate in the closed ear. Have an assistant manage the fork, and close the ears alternately. Something of the same kind happens when a deep note is sung; close first one ear and then both, and notice the passage of the tone from the throat to the ear and finally to the middle of the head.

b. Have an assistant manage the fork, and close both ears. Notice that when the fork is pressed on so as to make the tone loud the intercranial location is exact, but when the pressure is relaxed and the tone is faint the location tends to be extracranial.

c. Try setting the fork on other places than the vertex. Notice that in the occipital and parietal regions the sound appears in the opposite ear, though closing the ear as in *a* may bring it back to the same side as the fork.

d. Take a long pencil in the teeth like a bit and rest the stem of a vibrating tuning-fork vertically on it near one end and close the ear on the other side; the sound will seem to be located in the closed ear. Then gradually tilt the fork backward toward a horizontal position, keeping it in contact with the pencil, till its tip is opposite the open ear. The tone will change its place from the closed to the open ear.

On *a* and *b*, Schaefer, *B* and *C*; on *c*, Thompson.

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For the Stumpf-Wundt discussion on pitch distances consult the following: Stumpf, *Zeitschrift für Psychologie*, I., 1890, 419; II., 1891, 266, 426, 438; Engel, *Ibid*, II., 1891, 361; Wundt, *Philos. Studien*, VI., 1890-91, 605; VII., 1891, 298, 633; also Münsterberg, *C*, above.

CHAPTER V.

The Mechanism of the Eye and Vision in General.

THE mechanism of the eye accomplishes two things: the projection of a sharp image on the retina, and the ready shifting of the eye so as to bring successive portions of the image into the best position for seeing. To the study of these mechanisms and other physiological phenomena of importance for the psychology of vision, this chapter is devoted.

THE RETINAL IMAGE AND ACCOMMODATION.

104. The Retinal Image. This is easily seen in the unpigmented eye of a pink-eyed rabbit.

a. Chloroform the rabbit, remove the eyes, and mount them in clay for readier handling. The mounting is done as follows: Make a thick ring of clay with an internal diameter a little greater than that of the cornea of the rabbit's eye; place the eye, cornea downward, in the ring; lay a similar ring upon it to keep it in place, and press the edges of the rings together. The eye can now be handled easily and turned in any direction. Turn the cornea toward the window, and observe, from behind, the inverted image on the retina. Bring the hand into range and move it to and fro; observe that the image of distant objects is more distinct than that of the hand. The dead eye is adjusted for distant vision. If convex and concave lenses are at hand (spectacle lenses will answer), bring them before the eye, and observe that the effect upon the

retinal image is similar to that seen subjectively when they are held before the observer's own eye, provided that that is normal.

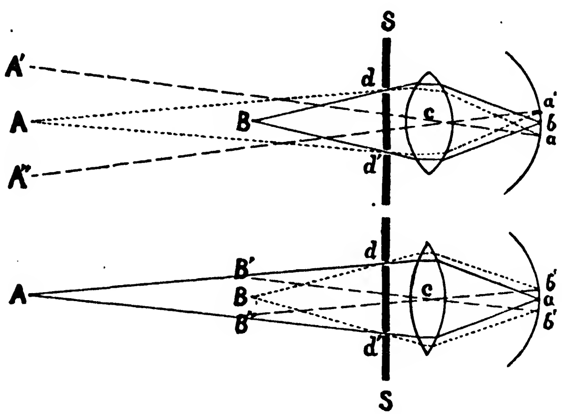
Reverse the eye, holding it retina side toward the window, and observe the radiating and circular fibres of the iris. The eye must be fresh, for if long removed it loses its transparency.

105. Accommodation. The sharpness of the retinal image depends on the adjustment of the crystalline lens, which must be such as to focus upon the retina the light from the object under regard. The lens must be thicker and rounder for near objects, thinner and flatter for more distant ones. These adaptations of the eye are known as *Accommodation.* The changes in the clearness of the retinal image are easy to observe subjectively. Hold up a pin or other small object six or eight inches away from the eyes. Close one eye and look at the pin with the other. The outline of the pin is sharp, but the outlines of things on the other side of the room behind it are blurred. Look at these, and the outline of the pin becomes blurred. Notice the feeling of greater strain when looking at the nearer object. The experiment is somewhat more striking when the nearer object is a piece of veiling or wire gauze, and the farther, a printed page held at such a distance that it can just be read.

On this and the next two experiments, see Helmholtz, *A*, 112–118, Fr. 119–126 (90–96).

106. Scheiner's Experiment. *a.* Pierce a card with two fine holes separated by a less distance than the diameter of the pupil, say, a sixteenth of an inch. Set up two pins in corks, distant respectively eight and twenty inches from the eye in the line of sight; close one eye, and holding the card close before the other with the holes in the same hori-

zontal line, look at the nearer pin; the farther pin will appear double. Look again at the nearer pin, and while looking, cover one of the holes with another card; one of the images of the farther pin will disappear — the left when the left hole is covered, and the right when the right is covered. Look at the farther pin or beyond it; the nearer pin appears double. Repeat the covering; closing the left hole now destroys the right image, and covering the right destroys the left.



Why this should be so will be clear from the diagrams above. The upper diagram illustrates the course of the rays of light when the eye is accommodated for the nearer pin; the lower diagram when it is accommodated for the farther pin. *A* and *B* represent the pins; *S* and *S* the pierced screen; *d* and *d'* the holes in the screen; *c* and *c* the lens; *a' b a''* and *b' a b''* the retinæ; *A'*, *A''*, *B'* and *B''*, the positions of the double images. The solid lines represent the course of the rays from the pin that is accommodated for; the lines of short dashes, the course of the rays from the other pin;

the lines of long dashes, the *lines of direction*; i.e., approximately those giving the direction in which the images appear to the observer. In the upper diagram the rays from B are focused to a single retinal image at b, while those from A, being less divergent at first, are brought to a focus nearer the lens, cross over and meet the retina at a' and a'', and, since each hole in the screen suffices to produce an image, cause the pin to appear double. Its two images are referred outward as all retinal images are, along the lines of direction (which cross a little forward of the back surface of the lens, in the *crossing point of the lines of direction*), the right retinal image corresponding with the left of the double images and *vice versa*. If now the right hole (d) in the screen be closed, the left retinal image and the right double image disappear. The case of accommodation for the farther pin will be clear from the lower diagram, if attention is given to the dotted and dashed lines. It will also be easy to explain why moving the card when looking through a single pin-hole causes apparent movements of the pin not accommodated for, and why in one case the movement seems to be with the card, and in the other case against it.

b. Stick the pins into the corks so that they shall extend horizontally, and examine them with the card held so as to bring the holes one above the other.

c. Arrange the holes thus: . ˙ . and observe that the triple image of the nearer pin (when the farther is fixated) has the reverse figure ˙ . ˙

Scheiner's experiment can easily be illustrated with any convex lens and a pierced screen of suitable size.

107. Range of Accommodation. *a.* Find by trial the nearest point at which a pin seen as in Scheiner's experiment can be seen single. This is the *near point* of accom-

modation. For the short-sighted a *far point* may also be found, beyond which double images reappear.

b. Find how far apart in the line of sight two pins may be, and yet both be seen single at one and the same time. Try with the nearer at 20 cm., at 50 cm., at 2 m. That portion of the line of sight, for points in which the same degree of accommodation is sufficient, is called the *Line of Accommodation.* The length of the line increases rapidly as the distance of the object from the eye increases.

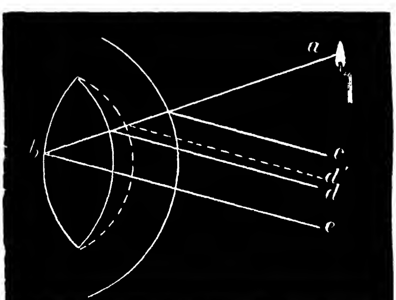
Helmholtz, *A*, 114, 119, Fr. 122 (93), 128 (97).

108. Mechanism of Accommodation. The change in the lens in accommodation is chiefly a bulging forward of its anterior surface. This may be observed as follows: —

a. Let the subject choose a far and a near point of fixation in exactly the same line of vision; close one eye and fix the other upon the far point. Let the observer place himself so that he sees the eye of the subject in profile with about half the pupil showing. Let the subject change his fixation at request, from the far to the near point, and *vice versa*, being careful to avoid any sidewise motion of the eye. The observer will notice, when the eye is accommodated for the near point, that more of the pupil shows and that the farther side of the iris seems narrower. This change is due to the bulging forward of the front of the lens. If the change were due to accidental turning of the eye toward the observer, the farther edge of the iris should appear wider instead of narrower. Notice also that the diameter of the pupil changes with the accommodation.

b. Purkinje's Images. The changes in the curvature of the lens may also be observed by means of the images reflected from its front and back surfaces and from the front of the cornea. Operate in a darkened room. Let the subject choose far and near fixation points as before. Let the

observer bring a candle near the eye of the subject at a level with it and a little to one side, and place his own eye in a position symmetrical to the candle on the other side of the subject's line of sight. Careful examination and some shifting about of the place of the candle and of the observer will show three reflected images of the flame: one on the side of the pupil next the light, easily recognizable, bright and erect, reflected from the surface of the cornea; a second, nearer the centre of the pupil and apparently the farthest back of the three, erect like the first, but very indistinct (more like a light cloud than an image), reflected from the anterior surface of the lens; and a third, a mere point of light, near the side of the pupil farthest from the flame, inverted and reflected from the posterior surface of the lens. When the observer has found these three images, the subject should fixate alternately the near and far points chosen. As he fixates the near point, the middle image will grow smaller, advance, and draw toward the corneal image; when he fixates the far point, the image will enlarge, recede, and move away from the corneal image. The following diagram, after Aubert, illustrates the movement of the middle image; the full lines indicate the positions of the cornea and lens and the course of the rays of light when the eye is accommodated for the far point; the dotted lines indicate the anterior surface of the lens and the direction of the ray reflected from its surface when the eye is accommodated for the near point. Three images similar to those in question can be



observed on a watch glass and a double convex lens held in the relation of the cornea and crystalline.[1]

Helmholtz, *A*, 131–141, especially 131–134, Fr. 142–154 (104–112), especially 142–146 (104–107); Aubert, *A*, 444; Tscherning.

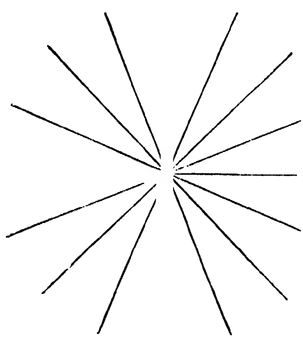
109. Dioptrical Defects of the Eye. Of these defects only two will be considered here: *Astigmatism* and *Chromatic Aberration.* The first is an error in the form or setting of the refracting surfaces, which prevents their bringing parallel light to a focus in a single point. If the curvature of the lens, for example, (or of the cornea), is greater on the vertical meridian than on the horizontal, parallel light falling upon the first will be brought to a focus nearer the lens than that falling upon the second. This makes it impossible for the astigmatic eye to see all parts of a plane figure with equal distinctness at the same time. *Chromatic Aberration* depends upon the different degrees of refraction which different colored lights experience in traversing the lens; those of short wave-length (violet and blue) are most refracted, those of long wave-length (red and orange) least, and the others in order between. The point at which parallel violet rays are brought to a focus is therefore nearer the lens than the point for red. In order, therefore, that the same degree of accommodation may serve to show a red lighted object and a violet lighted object at the same time and both with full distinctness, the red light must be less divergent than the violet; in other words, the red lighted object must be somewhat farther away.

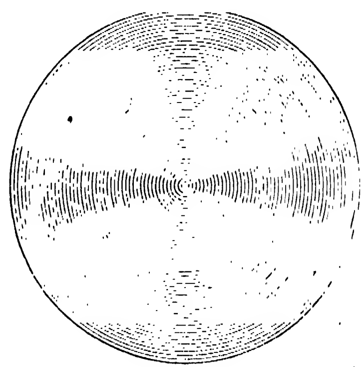
a. Astigmatism. Make a fine pin-hole in a card; hold it at arm's length against a bright background and accommo-

[1] By using a magnifying-glass a second faint corneal image very close to the first can be seen, when the light strikes the cornea well toward one side. When this is counted, as it is by Tscherning, there are four Purkinje images, those from the front and back of the lens becoming the third and fourth in the enumeration, instead of the second and third.

date the eye for a nearer point, or put on convex glasses. The spot will not appear as a little circle of light, as it would if the lens and cornea were perfect in form, but as a more or less irregular star or flower-shaped figure in which portions of several images of the hole may be made out. Accommodate for a point considerably beyond the card and notice the change in the figure.

These irregularities (phenomena of *Irregular Astigmatism*) disappear, however, with exact accommodation, but another kind (*Regular Astigmatism*) is then to be observed. Close one eye and look with the other at the centre of the radiating figure below. Notice which lines appear with greatest blackness and distinctness. Try the effect of increasing and decreasing the distance. Try also the other eye.





Something of the same kind is to be seen in the set of concentric circles; also evidences of irregular astigmatism when accommodation is changed or when the distance of the diagram is increased or decreased. Notice especially the rayed appearance and the distortion of the inner circles when the eye is accommodated for a greater distance than

that of the diagram. On the latter peculiarity, see von Bezold.

b. Chromatic Aberration. Bend a fine platinum wire into a ring half an inch in diameter, and heat it white hot in the flame of a Bunsen burner. Look at the ring through a pin-hole in a black card held at such a distance that the ring lies close to the edge of the field of the pin-hole all around. Accommodate the eye for the centre of the ring, and observe that the outer edge of the ring appears bright red, the inner edge blue or violet. Substitute for the card a bit of blue glass, and accommodate first for the glass, then for a point some distance beyond the ring. In the first case the outer and inner edges of the ring (except as astigmatism interferes) will both be blue; in the second case they will be red. The ordinary blue glass allows both red and blue light to pass through it.

Look at the edge of the window frame next the pane, and bring a card before the eye so that about half the pupil is covered; if the card has been brought up from the frame side, the frame will be bordered with yellow; if from the pane side, with blue. In ordinary vision these fringes do not appear, because the colors partially overlap and produce a practically colorless mixture.

Von Bezold's Experiment. Look at the parallel lines of the left figure in Ex. 118 with imperfect accommodation, e.g., through convex spectacles, and observe the aberration colors. If a set of heavy concentric circles (separated by equal spaces, and beginning with a central black dot of a diameter equal to the width of the lines) is used instead of the straight line figure, it will be possible by changing its distance from the eye to find a position in which the aberration colors so overlap that dark and light seem to have changed places, and the central spot is light instead of dark. The spiral figure with Ex. 128 will show

something of the effect, but the central black spot is too large to show it completely.

Both astigmatic differences and the aberration colors may at times influence judgments of distance.

On *a*, Helmholtz, *A*, 169 ff., Fr. 187 (138) ff. On *b*, Helmholtz, *A*, 156–164, Fr. 172–179 (125–131); von Bezold; Tumlirz.

Entoptic Appearances.

110. Floating Particles in the Media of the Eye and on its Surface; *Muscæ Volitantes.* Fix a lens of short focus at some distance from a bright gas or candle flame. Set up in the focus of the lens a card pierced with a very fine hole; bring the eye close to the hole and look toward the light. The eye should be far enough from the hole to prevent the edge of the lens from being seen. The rays of light that now reach the eye are strongly divergent, and the crystalline lens does not bring them to a focus on the retina, but only refracts them to such a degree that they traverse the eye nearly parallel, and thus in suitable condition for casting sharp shadows upon the retina of objects on or in the eye.

a. The lens will appear full of light, and in it will be seen a variety of shadings, blotches, and specks, single or in strings, the outward projection of the shadows just mentioned. The figures in this luminous field will vary from person to person, even from eye to eye, but in almost every eye some will be found that move and some that remain fixed or only move with the eye. Of the moving figures some are due to particles and viscous fluids on the surface of the eye; they seem to move downward, and are changed by winking. Notice, for example, the horizontal bands that follow a slow dropping and raising of the upper lid. Such appearances as these, since their cause is not really in the eye but outside of it, have been called *pseudentoptic* by Laqueur. Others, the *muscæ volitantes,* are frequently

noticed without any apparatus; they appear as bright irregular threads, strings of beads, groups of points, or single minute circles with light centres. They seem to move downward in the field, but actually move upward in the vitreous humor where they are found. Of the permanent figures, some are due to irregularities of structure or small bodies in the crystalline and its capsule (spots with dark or bright centres, bright irregular lines, or dark radiating lines corresponding probably to the radial structure of the lens); others of a relatively permanent character, it is said, can be produced on the cornea by continued rubbing or pressure on the eyeball.

b. The round spot of light in which these things are seen represents the pupil, and the dark ground around it is the shadow of the iris. Notice the change in the size of the spot of light, as the eye is accommodated for different distances (cf. Ex. 108), or as the other eye is exposed to, or covered from, the light. The change begins in about half a second. It shows the close connection of the iris mechanisms of the two eyes, and is typical of the way in which the two eyes co-operate as parts of a single visual organ.

Some of these entoptic observations may be made with a pierced card alone, or simply by looking directly at a broad expanse of clear sky without any apparatus at all.

Helmholtz, *A*, 184–192, and Tafel I., which shows the appearance of several of these entoptic objects, Fr. 204–214 (149–156) and Pl. V., also 548–558 (419–427); Laqueur.

111. Retinal Blood-vessels, Purkinje's Vessel Figures. *a.* Concentrate a strong light (preferably in a dark room), or even direct sunlight, with a double convex lens of short focus on the sclerotic in the outer corner of the eye of the subject, requesting him to turn the eye toward the nose

and giving him a dark background to look toward. Make the spot of light on the sclerotic as small and sharp as possible, and give to the lens a gentle to and fro or circular motion. After a little the subject will see upon the field, which the light makes reddish-yellow, the dark branching figure of the shadows of the retinal vessels. Notice that the spot directly looked at is partially surrounded, but not crossed, by the vessels. In this lies the yellow spot (*macula lutea*), the retinal area of clearest vision. The centre from which the vessels radiate lies in the point of entrance of the optic nerve. In this form of the experiment the light radiates in all directions within the eye from the illuminated point of the sclerotic.

b. Somewhat the same sort of image is to be secured by moving a candle about near the eye, below it and a little to one side. In this experiment some indication of the region of the yellow spot is to be seen. This time the light enters by the pupil, forms an image on a part of the retina somewhat remote from the centre, and this retinal image is itself the source of the light by which the vessel shadows are cast.

c. Look through a pin-hole in a card, held close before the eye, at the sky or some other illuminated surface, or at a broad gas-flame. Give the card a rather rapid circular motion, and the finer retinal vessels in the region of the yellow spot will readily be seen, among them also a small colored or slightly tinted spot (best seen, perhaps, by gas-light) representing the *macula*, and in its centre a shadowy dot (representing the *fovea*, the point of clearest vision). which appears to rotate when the motion of the card is circular. If the card is moved horizontally, the vertical vessels alone appear; if vertically, the horizontal vessels. Notice also the granular appearance of the *macula;* the granulations have been supposed to represent the visual

cones of that region. The finer retinal vessels can also be seen when looking at the vacant field of a compound microscope, if the eye is moved about rapidly.

In all cases it is important that the shadows be kept moving; if they stand still, they are lost. The explanation is partly physiological (the portions of the retina on which the shadows rest soon gain in sensitiveness enough to compensate for the less light received) and partly psychological (moving objects in general arouse spontaneous attention, and those whose images rest continuously on the retina without motion are particularly subject to neglect).

Once having become familiar with these vessel figures, it is often possible for the observer to see traces of them without any apparatus. Parts of them, with something of the yellow spot, may sometimes be seen for an instant as dark figures on the diffusely lighted walls and ceiling, or as light figures on the dark field of the closed eyes, when the eyes are opened and closed after a glance at the window on first waking in the morning, or as blue figures when looking at the snow and winking on a bright winter morning.

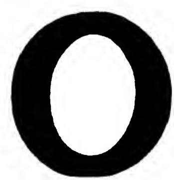
Helmholtz, *A*, 192–198, 555, Fr. 214–221 (156–161), 528 (402).

112. Retinal Circulation. Look steadily through two or three thicknesses of blue glass at the clear sky or a bright cloud, and observe the bright points darting hither and thither like bees in a swarm or snowflakes on a windy day. Careful observation will also establish that the bright points are followed by shadowy darker ones. Pick out a speck on the window to steady the eyes, and observe that while the movements of the points seem irregular the same lines are retraced by them from time to time. When several of their courses have been accurately determined for one of the eyes, repeat the experiment for demonstrating the finer retinal vessels (Ex. 111, *c*), and notice that fine vessels

are found which correspond to the courses that the points seem to follow. These flying points can be seen without the glass by a steady gaze at an evenly lighted bright surface, and sometimes a rhythmical acceleration of their movements will be found, corresponding to the pulse. Helmholtz explains the phenomenon by a temporary clogging of fine capillary vessels by large blood corpuscles. The bright lines (the apparent tracks of bright points) are really the relatively empty capillary tubes ahead of the corpuscles, which, after an instant, are driven onward by others crowding behind, which in turn give the shadow that apparently follows the bright points.

Helmholtz, *A*, 198 f., Fr. 221 (337), 555 (425); Rood.

113. The Blind Spot. Mariotte's Experiment. The point of entrance of the optic nerve is unprovided with visual end-organs and is irresponsive to light. This insensitiveness is easily demonstrated with the diagrams below.



a. Close the left eye, and keeping the right fixed on the upper asterisk in the diagram move the latter toward the eye and away from it till a point is found where the black oval disappears. For the blind spot of the left eye, turn the diagram upside down and close the right eye.

The blind spot may be demonstrated simultaneously in both eyes with the figure on the next page. The experimenter should look at the asterisk while he holds a card

in the median plane of his head, to prevent each eye from seeing the other's part of the diagram.

b. To draw the projection of the blind spot, arrange a head-rest opposite a vertical sheet of white paper, and 15 or 18 inches distant from it. Put a dot on the paper for a fixation point. Fasten upon the end of a light rod a bit of black paper about 2 mm. square or blacken the end of the rod with ink. Bring the face into position, close one eye, and fix the other upon the dot. Move the rod slowly so as to bring the little square over the part of the paper corresponding to the blind spot, dotting on the paper the points where the square disappears or reappears. Repeat at various points till the outline of the projection of the blind spot is complete. If the mapping is carefully carried out, the map will probably also show the points of departure of the large blood-vessels that enter with the nerve.

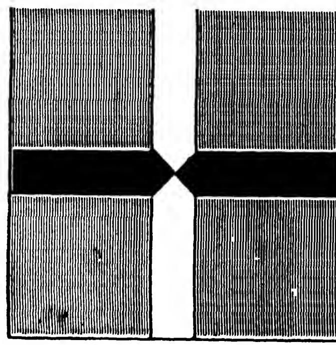
Helmholtz, *A*, 250–254, Fr. 284–289 (210–214).

114. The Filling-out of the Blind Spot is of considerable psychological interest. The mind supplies what is lacking in the sense, and in doing so is influenced both by the sensations of the parts of the retina surrounding the spot and by previous experience. In ordinary two-eyed vision the blind spot of one eye corresponds to a seeing spot in the other, and this with the movements of the eyes amply supplies the defect. The spot, furthermore, lies so far out of the range of clear vision that its existence is habitually overlooked, even in monocular vision.

a. When the image of the oval in *a* of the last experi-

ment is brought wholly upon the spot, the paper seems an unbroken white, because the adjacent parts of the retina are stimulated with white. When, however, the diagram is held a little nearer so that the edge of the black oval can be seen, the filling is part black and part white.

b. The effect of experience appears when the oval is replaced by such a figure as that below, or any other in which the bars stand out well from one another and the background.



When the image of the middle of this diagram falls upon the blind spot, one bar will seem to cross completely over the other. Bars that cross are so much more frequent in experience than those that are mitered together that the sensations of the adjacent parts are thus interpreted. Skill in observation in indirect vision seems to hinder this filling-out process somewhat, probably by aiding in more exact distinguishing of the character of the sensations received. Both Helmholtz and Aubert find themselves unable to determine how the parts of the figure resting on the blind spot are related.

Helmholtz, *A*, Fr. 734–745 (574–583); Aubert, *A*, 595

115. The Yellow Spot, the *Macula Lutea.* The projection of the yellow spot in the visual field can be made visible in several ways. Two have already been mentioned in Ex. 111; others are as follows: Close the eyes for a few seconds and then look through a flat-sided bottle of chrome alum solution at a brightly lighted surface or at the clear sky. In the blue-green solution a rose-colored spot will be seen which corresponds to the yellow spot. The light that comes through the chrome alum solution is chiefly a mixture of red and green and blue. The pigment of the yellow spot absorbs a portion of the blue and green and transmits the rest, which makes a rose-colored mixture, to the visual organs behind it. The same can be very beautifully demonstrated with violet or purple gelatine sheets.

Helmholtz, *A*, Fr. 548–551 (419–421); Maxwell; Sachs; Hering, *C.*

116. Intermittent Illumination. The region of the yellow spot can be seen, together with many other curious figures and patterns, when the illumination of a single eye is made intermittent by moving the spread fingers rapidly to and fro before it. Something may be seen when the open eyes are fixed on a uniformly lighted surface, but more when they are turned with closed lids toward a bright sky or the sun itself. The figures probably differ in different eyes and some are beautiful and elaborate. Sometimes with steady fixation the figures give place more or less completely to a general streaming of fine particles, suggesting the flying specks of Ex. 112, but finer and of less regular course. Vierordt credited the appearance to the circulation of the blood in the retinal vessels; Helmholtz is inclined to think the fine particles lymph corpuscles rather than blood corpuscles. Similar phenomena are to be observed with black and white disks when rotated at less speed than that required for uniform mixing of the black and white.

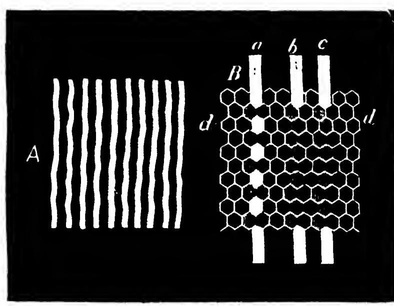
Helmholtz, *A*, 532 f., Fr. 502 (381) f.; Exner, *F.*

117. Acuteness of Vision, *Minimum Visibile.* *a.* Place the parallel line diagram used in Ex. 118 in a good light and walk backward from it till the lines can just no longer be distinguished as separate. If the experimenter's eyes are not normal, he should use glasses that fit his eyes for distinct vision at the distance required. Measure the distance between the eye and the diagram, and calculate the angle whose apex lies in the crossing point of the lines of direction (about 7.2 mm. back of the cornea and 15.6 mm. in front of the retina) and whose base is the distance from the middle of one line of the diagram to the middle of the next; in this diagram 1.6 mm. This angle measures the least visible extent when discrimination is involved; the least luminous extent that can still impress the retina is far smaller, as witness the visibility of the stars. On the supposition that if the sensations of two cones are to be separable they must be separated by an unstimulated cone, or at least by a less stimulated one, it has generally been considered that the cones could not subtend a greater angle than that found in this experiment, 60″—90″, representing 0.004—0.006 mm. on the retina, and this agrees well with microscopical measurements. But as Helmholtz notices (*Phys. Opt.*, 2d ed., p. 260), this experiment does no more than prove that there are on the retina rows of sensitive elements, the middle lines of which are separated by the angular distance found in the experiment. The elements themselves, if properly arranged, may be somewhat larger. Calculation of the number of such elements in a sq. mm. of the retina, based on this view of the experiment, agrees well in the case of Helmholtz's own determination with the result of microscopical counting.

b. The discriminative power of the retina falls off rapidly in all directions from the *fovea* — more rapidly above and below than in a horizontal direction. Arrange a head-rest

and perpendicular plane as in Ex. 113, *b* (or if a perimeter is at hand use that). Place upon the end of the rod used in that experiment a card on which have been made two black dots 2 mm. in diameter and 4 mm. from centre to centre. Move the card horizontally toward the fixation point, beginning beyond the point at which the two dots can be distinguished and moving inward till they can just be distinguished. Measure the distance from the fixation point, and repeat several times both to the right and left of the fixation point, holding the card so that both dots are in each case equally distant from that point. Try the same for the vertical meridian.

Helmholtz, *A*, 255–264, Fr. 291–301 (215–223); Uhthoff. On *a*, Aubert, *A*, 579–585; on *b*, 585–591. On *b*, see also Exner, *D*, 24.? ff.



118. Bergmann's Experiment. Place the left hand diagram in a good light, and look at it from a distance of a yard and a half or two yards. Observe the apparent bending and beading of the lines. This is believed by Helmholtz to be due to the mosaic arrangement of the visual cones. The cones that are touched by the image of one of the white lines are stimulated in proportion as they are more or less touched. Those that are much stimulated furnish the sensation of the white line and its irregularities; those that are little

stimulated join with those that are not touched at all to give the image of the black line and its irregularities. This is schematically represented in the right hand cut. Von Fleischl, on the other hand, has made experiments to show that the bending and beading of the lines is not connected with the retinal mosaic, but rather with movements of the eyes that sweep the point of fixation backward and forward across the lines. Further than this his explanation does not go.

Helmholtz, *A*, 257–258, Fr. 293 294 (217–218); von Fleischl.

119. Mechanical Stimulation of the Retina. *a.* Phosphenes. Turn the open or closed eye as far as possible toward the nose and press on the eyelid at the outer corner with the finger or the tip of a penholder. On the opposite side of the visual field will be seen a more or less complete circle of light surrounded by a narrow dark band, outside of which again is a narrow band of light. Notice the color of the light seen. Get phosphenes by pressure at other points of the eyeball.

b. Press the eye moderately with some large object, say, the angle of the wrist when the hand is bent backward, and continue the pressure for a minute or two. Peculiar palpitating figures will be observed and strange color effects. The former Helmholtz compares to the tingling of a member that is "asleep."

c. Standing before a window, close the eyes and turn them sharply from side to side. As they reach the extreme position in either direction, observe immediately in front of the face a sudden blue spot surrounded by a yellow band. A second fainter spot farther from the centre in the direction of motion may also be seen. The appearance of the first spot is due to a mechanical stimulation of a portion of the retina at the edge of the blind spot in the eye that turns

inward. The second spot belongs to the corresponding area in the other eye.

Helmholtz, *A*, 235–239, Fr. 266–270 (196–200), 744 (583) f.

120. Idio-retinal Light, Light Chaos, Light Dust. *a*. Close and cover the eyes so as to exclude all light, taking care not to press them, or experiment in a perfectly dark room. Let the after-effects of objective light fade away, and then watch the shifting clouds of retinal light. The cause of the retinal light is not altogether clear, but it is supposed to be a chemical action of the blood on the nervous portion of the visual apparatus. Aubert estimates its brightness at about half the brightness of a sheet of paper illuminated by the planet Venus when at its brightest.

b. When awake in the night time in a room that is almost perfectly dark (e.g., in which the form of the window and the large pieces of furniture cannot be made out), notice that the white clothing of the arms can be seen faintly when they are moved about, but not when they are still. In the last case the very faint light they reflect is not sufficient to make them distinguishable from clouds of idio-retinal light.

Helmholtz, *A*, 242–243, Fr. 274–275 (202–203). On *b*, Helmholtz, *B*.

121. Electrical Stimulation of the Visual Apparatus. Moisten thoroughly with salt water both the electrodes and the portions of the skin to which they are to be applied. Place one of the electrodes on the forehead (or on the edge of the table and lay the forehead upon it), the other on the back of the neck; or, if the current is strong enough, hold it in the hand or lay it on the table with the hand upon it. At each opening or closing of the circuit, a bright flash will be seen, whether the eyes are closed or open. With the eyes closed and covered, the effects of the continuous current

may be observed. In this case it is well to apply the electrode slowly and carefully so as to avoid as much as possible the flash caused by the sudden closing of the circuit. When the positive electrode is on the forehead, the negative on the back of the neck, a transient pale violet light will be seen distributed generally over the field and forming a small bright spot at its centre. Sometimes traces of the blind spot also appear. The violet light soon fades, and on opening the circuit there is a notable darkening of the field, with a momentary view of the blind spots as bright disks. When the negative electrode is on the forehead, the positive on the back of the neck, the phenomena are in general reversed, the darkening occurring on closing the circuit, the violet light on opening it. Helmholtz sums up these and other experiments in the following law: "Constant electrical circulation through the retina from the cones toward the ganglion cells gives the sensation of darkness; circulation in the contrary direction gives the sensation of brightness." (*Phys. Opt.*, 2d ed., p. 247.) That the blind spot should appear as a disk of different color from the rest of the field seems to be due to the fact that the sensitive parts of the retina immediately surrounding it are somewhat shielded from the electric current, and as usual their condition is attributed to the blind spot also. The experiment is not altogether a pleasant one, on account of the feeling which the current produces in the head, the "electrical taste" in the mouth, and the reddening of the skin under the electrodes.

Helmholtz, *A*, 243–248, Fr. 275–281 (203–207), 744 (583).

Retinal Fatigue and Adaptation.

122. Retinal Fatigue. Stare with perfectly fixed and motionless eyes at a selected spot on a variegated carpet or wall paper, and notice the levelling effect of fatigue. The

differences in color and pattern gradually disappear, and the whole field becomes a nearly uniform cloud. The parts of the retina that are strongly stimulated are brought down to the general level; those that are little stimulated are built up to it. Every wink or slight movement of the eyes causes a general brightening up of the field and restoration of vision. The experiment is particularly easy to make when looking at a uniform surface with faint shadows lying on it.

Helmholtz, *A*, 508, 555 ff., Fr. 478 (362), 527 (402) ff.; Fick, *B*, 222; Treitel; Hering, *C*. See also the discussion on this topic by A. E. Fick and Hering.

123. Adaptation of the Eye. *a*. The adjustment of the eye to the intensity of its illumination is effected partly by change in the size of the pupil, and partly by changes in the retina itself. The first is of common observation, and the connection of the two eyes in this respect has been noticed in Ex. 110, *b*. The effects of going from a dark room into a light room and *vice versa*, and the gradual improvement of vision on remaining in one or the other, are also familiar.

b. It has not, however, been so generally observed that adaptation to very weak lights is much more favorable to the perception of colorless light than to colored. This may easily be observed in a dark room with single flashes of a rather faint Geissler tube. Before the room is darkened, and for a short time after, the colors of the light are readily perceived. After some time, however, they nearly or quite fail, seeming to be lost in the increased brilliancy of the white light. It is important that there should be an interval between the flashes sufficient to allow all the effects of one to disappear before another is given. If the room is not completely dark, the head of the observer and the tube

must be covered closely with an opaque cloth to allow full adaptation.

Aubert, *A*, 483 f., *B*, 25 ff.; Charpentier, *A*, 154 ff.; Treitel; Hering, *C*. On *b*, Hillebrand.

AFTER-IMAGES.

After-images, Accidental or Consecutive Images. After-images in which the relations of light and shade of the original object are preserved are called *Positive After-images*. Those in which these relations are reversed (as in a photographic negative) are called *Negative After-images*. Positive after-images are of various colors, but most important to notice here are those of the color of the object (*like-colored*), and of the complementary color (*opposite-colored*). Negative after-images, so far as observed, are always *opposite-colored*. All after-images, especially the positive, can best be observed in the morning when the eyes are well rested.

124. Negative After-images. *a*. Look steadily for a minute at a fixed point of the window, then at a white screen or an evenly lighted, unfigured wall; the dark parts of the window will now appear light and the light dark.

b. Get a lasting after-image and look at a corner of the room, or at a chair or other object of uneven surface; notice how the image seems to fit itself to the surface upon which it rests. After a little practice it is also possible at will to see the image floating in the air instead of lying on the background.

c. Look steadily at a bright-colored object or some bits of colored paper, then at the screen; observe that the colors of the after-images are approximately complementary to the colors of the objects producing them.

d. Negative After-images upon a Background faintly Tinged with the Stimulating Color. Fasten upon the color-mixer a

white disk upon which has been painted a six rayed star of red. Set the disk in rapid rotation, bring the eyes within eight or ten inches of the disk, and after half a minute suddenly withdraw them to thirty or forty inches. As the head is drawn back the complementary color will be seen to press in upon the disk from all sides while the red contracts. When the head is again approached to the disk the red will enlarge and the blue-green disappear. The cause of the rushing in of the blue in the first case is the contraction of the retinal image, which of course decreases in size as the head is drawn back, and is thus brought upon parts of the retina that have been more strongly stimulated. When the head approaches the disk the retinal image enlarges and its outer portion lies on a fresh area.[1]

Negative after-images are sometimes very lasting, and for that reason are those most frequently noticed in ordinary experience. They are phenomena of retinal fatigue (Helmholtz), or of retinal restitution (Hering).

125. Positive After-images. These images are not difficult to see, if after a brief stimulation the eye is shielded from further action of light. Thus, when the gas is suddenly turned off in a dark room, the positive image of the flame and the burner is very easily seen.

a. Look for an instant (one-third of a second) at the window, then close and cover the eyes. Notice that the after-image is like the window in distribution of light and shade, bright panes and dark bars, and at first like it also in color. After some practice it is also possible to see, for a small fraction of a second, the positive after-image of almost any bright object on suddenly turning the eyes from the object to some other part of the field, especially if the latter is dark. The positive after-image is of short duration and less readily observed than the negative. It has generally

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[1] For a still simpler experiment, see *Mind*, Ser. 2, II., 1893, 485, note.

been considered a phenomenon of retinal inertia, a prolongation of the original retinal excitation, and such a prolongation does undoubtedly exist. Charpentier and Hess, however, in experiments with very brief stimulation, have found a transient negative image coming between the original impression and the ordinary positive after-image observed with longer stimulation. The full series would then be: 1. Prolongation of the original stimulus; 2. First Negative Image; 3. Ordinary Positive After-image; 4. Ordinary Negative After-image.

b. Colored Positive After-images. Look for an instant at a gas flame through a piece of red glass, then close and cover the eyes and observe the red image; repeat the experiment, continuing the fixation of the flame for half a minute; the resulting after-image will be bright as before but of the opposite color.

c. After-images on Dark and Light Backgrounds. Get an after-image of the window of not too great intensity, and project it alternately on a sheet of white paper and the dark field of the closed and covered eyes; it will be found negative on the white background and positive on the dark. Some observers find a periodic reappearance of positive after-images, or an alternation of positive and negative images, without a change of background.

d. Sequence of Colors. Get a good after-image of the window, and observe with closed and covered eyes the play of colors as the image fades. Try several times and observe that the order of succession is the same. According to Hering, this play of colors would not take place if the original stimulus were absolutely colorless.

On Exs. 124 and 125, consult the following: Helmholtz, *A*, 480 ff., 501 ff., Fr. 446 (338), 471–500 (357–380); Wundt, *A*, 3te Aufl., I., 472–476, 4te Aufl., I., 512 ff.; Hess; Charpentier, *B*. See also references given in Chap. VI. for Successive Contrast.

126. **Effect of Eye-motions on After-images.** Get a moderately strong after-image of the window; look at the wall and keep the eyes actively in motion. The image will be seen with difficulty while the eye is in motion; when, however, the eye is brought to rest, it will soon appear. In general, any visual stimulus that moves with the eye is less effective than one that does not.

Exner, *A*.

127. The Seat of the After-image. An after-image due to stimulation of one eye may, under proper conditions, sometimes seem to be seen with the other. From this it has been inferred that the seat of after-images is central, not peripheral; that is, in the visual centres of the brain, higher or lower, not in the retina. The following experiments show, however, that the after-image is really seen with the eye first stimulated, and so render the hypothesis of a central location unnecessary.

a. Look steadily for a considerable time at a bit of red paper on a white ground, using only one eye, say the right, and keeping the other closed; when a strong after-image has been secured, remove the paper, close the right eye, open the left, and again look steadily at a fixed point on the white ground; after a little the field will darken and the after-image will reappear. If the red does not produce a sufficiently lasting image, substitute for it a gas flame or some other bright object.

b. That we have really to do with the eye originally stimulated (its present dark field suppressing the light one of the other eye), appears from such experiments as the following: Get the after-image as before; then open both eyes and bring a bit of cardboard before the eyes alternately. Bringing it before the left eye rather brightens the image; bringing it before the right dims or abolishes it.

The image is thus chiefly affected by what affects the right eye.

c. Get the after-image again, and close and cover both eyes; observe the color of the after-image, as projected on the dark field; then open the left eye, letting the right eye remain closed and covered. The after-image will be seen, not in the color it has when the right eye is open and the image is projected in the light field, but in that which it has in the dark field of the closed eye.

These experiments prove that after-images belong to the stimulated half of the visual apparatus, but they do not show whether the images belong to the retina of that half or to the nervous centres connected with it. Other considerations, such, for example, as the fact that the image follows every motion of the eye, even those that are usually unconscious, is affected by pressures exerted on the eyeball and by electric currents sent through it, together with Exner's direct experiments on retinal and optic nerve stimulation, support the retinal location, in favor of which current opinion is practically unanimous. Some observers, however, have been able to get a binocular after-image of a somewhat different character; see binocular section of Chap. VI.

Delabarre; Exner, *D*, 246 ff. and *E*; Fick and Gürber, 296 ff.

128. After-images of Motion. These after-images can be secured from almost any continuously moving object. They are often unpleasantly striking after looking at the water from the deck of a vessel or at the landscape from a car window. In the experiments below, variations of one of the laboratory methods of producing them are given.

a. Fasten upon the rotation apparatus a disk bearing a large number of equal black and white sectors; set it in slow rotation and gaze fixedly at it. The rate must not

be fast enough to blur the outlines of the sectors very much. After a moment or two of steady fixation, bring it suddenly to rest and observe its slow illusory backward movement.

b. Fasten on the apparatus a disk like that in the accompanying cut, and get an after-image as before, fixating the centre. Bring the disk suddenly to rest, or look away from it to a page of print or into the face of a bystander and notice the apparent shrinking or swelling, reversing the previous motion of the spiral. Illusions of increase or decrease of distance sometimes accompany those of motion with this disk. Repeat the experiment, but this time instead of looking at some object, close the eyes and turn them toward the sky or other source of bright light. The apparent motion will be observed again in the red-yellow field.

c. Hold over half of the disk while in rotation a piece of cardboard, fixate the centre of the disk, and get the after-image. Observe that the after-image is limited to the portion of the retina stimulated.

d. Get a monocular after-image of the spiral, with the right eye, for example. Then close the right eye and open the left; the after-image of motion will be projected like that of color in Ex. 127.

e. Hold just above the spiral disk a larger disk of pasteboard, cut with a radial slot an inch or two wide. When the spiral is now revolved a narrow strip will be seen in

which the motion is in one direction only. Get a strong after-image and observe it with closed eyes as in *b* above. It will sometimes be possible, at least for a short time, to get a reversal of the previous illusion; the part of the image corresponding to the slot will appear to stand still while the adjacent parts move, or both will appear in motion in opposite directions. This experiment is apparently easier to get with the antirrheoscope, where the moving field is larger. With that instrument the effect mentioned can be seen in the ordinary projected after-image.

When a strong after-image is projected upon a set of straight lines at right angles to the direction of movement, some observers have seen the lines more or less distorted by it (Budde saw them thus affected when the lines did not cross, but only entered the moving part of the field); others have found the lines entirely unaffected. It seems probable that the breadth and distinctness of the lines have something to do with this difference of results.

Exner, who believes in the retinal seat of color after-images, is inclined to give a more central location to these of motion. In his opinion such experiments as those above indicate also that our knowledge of such motions is a *sensation*, not a *perception*.

After-images of motion have been explained by actual, though unconscious, movements of the eyes, like the apparent movements of objects in dizziness. This is certainly incorrect; for in *b* it would seem necessary that the eyes should move in all directions at once, and *c* shows that the effect is limited to a portion of the field, which would be impossible if it were due to actual eye motions. The same was demonstrated by Dvorák by means of a disk with three concentric spirals, the inner and outer ones being drawn in the same way, (right-handed spirals, for example), while that between was drawn in the reverse direction. How far

some psychical representation of ocular motions co-operates in the illusion would be hard to say.

Helmholtz, *A*, Fr. 766–769 (603–605); Bowditch and Hall; Mach, *A*, 59–61 (see also 61–65 for yet another kind of after-image), and *B*, 65–67; Exner, *B* and *C*, 440 ff.; Dvorák; Budde; von Fleischl; Heuse; Zehfuss.

Movements of the Eyes.

The eye is a moving as well as a seeing member; and its motor functions are of great importance for psychology, especially for the theory of the visual perception of space. The experiences of the eye in motion have a controlling influence upon its perceptions even when at rest, as will appear in some of the experiments of Chap. VII.

All motions of the eye may be conceived as rotations of greater or less extent about one or more of three axes: a *sagittal axis*, corresponding nearly with the line of sight; a *frontal axis*, extending horizontally from right to left; and a *vertical axis*. Theoretically all these intersect at right angles in the *Centre of Rotation* of the eye. As a landmark from which to measure eye-movements, that position (approximately) is taken which the eyes assume when the head and body are erect and the eyes are directed forward to a distant horizon. This is known as the *Primary Position* of the eyes (or the lines of sight); any other is a *Secondary Position*. The point on which the eyes are fixed when in the primary position is the *Primary Fixation Point*, or *Principal Point of Regard*. The *Field of Vision* is the extent of space that can be seen with the eye at rest. The *Field of Regard* is the extent of space that can be seen when the eyes are moved. In the following experiments the word *Rotation*, except in the expression "centre of rotation," is reserved for turnings about the sagittal axis.

129. Reflex Movements of the Eye. Of the first importance among eye movements is the constant reflex tendency of the eye to move in such a way as to bring any bright image lying on a peripheral part of the retina, or any to which attention is directed, into the area of clearest vision. Many evidences of this tendency will be found in the ordinary course of vision. By way of experiment, try to study attentively a *musca volitans* or a negative after-image that is just to one side of the direct line of sight. The apparent motion of the object measures the energy of the reflex.

130. Associated Movements of the Eyes. The two eyes form a single visual instrument; and even when one eye is closed, it follows to a considerable degree the movements of its open companion. Movements upward or downward in normal vision are always performed simultaneously by the two eyes.

a. Close one eye, and, resting the finger-tip lightly on the lid, feel the motions of that eye as the other looks from point to point of the field of regard.

b. Get a monocular after-image, as in Ex. 127, and when it seems visible to the open eye, notice that it accompanies the fixation point of that eye as it moves from point to point of the field of regard.

Aubert, *A*, 651 ff.; Hering, *A*, 519 ff.

131. Motions of the Eyes when the Lines of Sight are Parallel. The movements here considered are somewhat simplified for easier exposition.

a. Donders's Law; the Law of Constant Orientation (Helmholtz); the Law of Like Position with Like Direction (Hering). It is evident that when the eye is fixed upon some point of its field, e.g., ten degrees upward and fifteen degrees to the right of the primary position, it is not thereby fixed

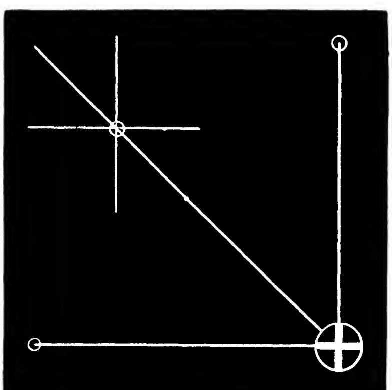
as regards its sagittal axis, but might conceivably assume an indefinite number of positions by different degrees of rotation about that axis. It might also, if not entirely free in its rotation, rotate now through one angle and now through another, depending on the direction in which the line of sight had moved to reach the position in which it is then found. As a matter of fact, however, it does not assume an indefinite number of positions, but one and only one, no matter by what movements the line of sight has come to that point. This is Donders's Law; and the fact that it expresses is of importance for sure and easy recognition of directions in the field of regard, and for deciding whether or not objects in the field have moved when the eye itself has been moved. The correctness of this law is easy to demonstrate.

Cut in a sheet of black cardboard two slits an eighth of an inch wide and four or five inches long, crossing at right angles. Set the cardboard in the window or before some other brightly lighted surface. Arrange a head-rest at a considerable distance, and when the head is in position, get a strong after-image of the cross, fixating its middle point. Then, without moving the head, turn the eyes to different parts of the walls and ceiling. The image will suffer various distortions from the different surfaces upon which it is projected, but each time the eye returns to the same point the image will lie as before. If the wall does not offer figures by which this can be determined, have an assistant mark the position of the image upon it. The after-image is of course fixed on the retina and can move only as the eye moves.

b. Listing's Law. This law goes beyond Donders's Law, and asserts that the position is not only fixed, but that in movements from the primary position there is no rotation at all about the sagittal axis. In other words, the final posi-

tion is such as the eye would assume if it were moved from its primary position to the position in question by turning about a fixed axis standing perpendicular at the centre of rotation to both the primary and the new position of the line of sight. To show this requires a little more care than the last experiment.

The observer must be placed at a distance of twenty-five or thirty feet from an extensive wall space, with a suitable head-rest as before. The lines of sight are, of course, not strictly parallel at this distance, but the difference may be neglected. On the wall stretch dark-colored strings as indicated in the accompanying diagram. The cross at the lower right hand corner should be approximately in the primary position for the observer. The longer vertical and horizontal strings should be twelve or fifteen feet long, the inclined one eighteen or twenty feet. The angle that the last makes with the others is not important so long as it is not too small with either. Fixation points of black cardboard or some other conspicuous substance should be affixed as indicated by the little circles. The cross in the corner may be made by pasting strips of bright-colored paper half an inch wide and a foot long on a disk of white cardboard, or (better still) it may be made by the line



of junction of four colored sectors, two red and two blue, for example The disk in either case must be so arranged that it can be turned about its centre and one of its diameters

be made to coincide with the oblique string. When all has been arranged make the following tests: —

Exact determination of the primary position. For most observers this is somewhat depressed below the horizontal position. Let the observer fixate the centre of the disk till he has secured a strong and clear-cut after-image of it and then turn his eyes, taking care not to move his head, to the fixation marks on the horizontal and vertical strings. If the corresponding lines of the after-image coincide with the strings, the head is in the required position. If not, the head must be moved a little to right or left if the error is with the vertical bar, and up or down if with the horizontal. The primary position differs a little from observer to observer, and even with the same observer at different times.

Having found the primary position, have an assistant turn the cross disk so that one of its diameters coincides with the oblique string. Get a clear after-image of it, and look at the fixation point on that string. Again the bar of the cross will lie exactly upon the string, thus showing that no rotation of the eye about the line of sight has taken place. The same would be true for any other direction of motion from the primary position, provided the movement were not of extreme extent. There is then a set of lines, radiating from the primary fixation point, along which the eye can move, so as to bring all parts of the same line successively on the same part of the retina. Direct examination of such a line and comparison of its parts is easy.

Restore the cross disk to its first position, incline the head forward or backward, or turn it to right or left before getting the after-image (thus bringing the eye into a secondary position), and repeat the experiments just made. Notice that the bars do not now coincide with the strings, showing that the eyes have suffered a certain amount of

rotation. Such a rotation appears for all secondary positions (except when the fixation point both at starting and ending lies in a straight line passing through the primary fixation point), but the extent of it is small in the ordinary movements of the eyes, and extreme movements are usually avoided by simultaneous movements of the head.

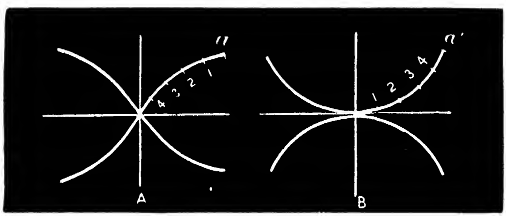
With the cross on the disk vertical as in the cut, get an after-image and fixate the mark on the oblique string. Instead of being rectangular as before, the after-image cross now appears somewhat distorted, like an oblique X. The after-image on the retina of course remains rectangular. The distortion of the image on the wall is the result of the interpretation now placed upon it by the mind. The short string cross at the same centre is known to be rectangular, and if the after-image cross fails to agree with it, the only harmonization of the two is that the latter is not really rectangular. Oblique crosses in such a position in previous experience have given rise to rectangular retinal images so often that this interpretation is immediate, and seems wholly a matter of sensation.

For a fuller account of Listing's Law see Appendix I.

Cf. Helmholtz, *A*, Fr. 601–609 (462–469), 621 (479) ff., 702 (548) ff.; Aubert, *A*, 653 ff.; Wundt, *A*, 3te. Aufl., II., 94 ff.; Hering, *B*, 248 ff.; Le Conte, 164–177.

132. Actual Movements of the Eyes. Wundt-Lamansky Law. Rapid motions of the eyes when they move freely and do not follow strongly marked lines in the field of regard, are not executed exactly according to Listing's Law, though that gives correctly the end positions reached. The axis about which the eye turns is not always constant, and the paths of the fixation point as it moves in the field of regard are therefore not all straight. This is easy to observe as follows. In a dark room turn down the gas till it burns in a very small flame. Then using this as a distant point

of departure in the primary position, look suddenly from it to other points of fixation in various directions about it, and notice the shape of the long positive after-images that result from the motion of the image of the flame over the retina. These will probably have the shape of the radii in the left hand figure below, the vertical and horizontal being nearly straight, and the oblique curved. These, however, do not show immediately the track of the fixation point. The newest part of the after-image is that next the light, the oldest part is that next the fixation point — at *a* in the diagram. If the points of the after-image curve are now interpreted in the order of time (taking the oblique curve to



the right and upward, for example), it appears that the eye at first moved rather rapidly toward the right, but rather slowly upward, while at last it moved rather slowly toward the right and rapidly upward. Plotting a curve in accordance with this interpretation, we get that given in *B*, which shows the true track of the fixation point. By similar plotting the other tracks may be found.

It is said that for some eyes the after-images, though curved, do not coincide with those figured in *A*.

Wundt, *B*, 139 ff., 201–202; Hering, *A*, 450–451; Lamansky.

133. Convergent Movements of the Eyes. The laws of Ex. 131 do not hold for convergent motions of the eyes.

When the lines of sight converge in the primary position, both eyes rotate outward; as the lines of sight are elevated, the convergence remaining the same, the outward rotation increases; as they are depressed, the rotation diminishes and finally becomes zero. On a sheet of cardboard draw a series of equidistant parallel vertical lines one or two inches apart and eight or ten inches long, drawing the left half of the group in black ink, the right half in red. Cross both sets midway from top to bottom by a horizontal line, red in the red set, and black in the black set. Fasten the cardboard flat upon a vertical support, and arrange the head rest in front of it. The horizontal line of the diagram should be on a level with the eyes.

a. If the operator is unable to control the degree of convergence voluntarily, he should fasten a bit of wire vertically between his eyes and the diagram in such a way that it can be moved to and from the eyes. If he is able to control the convergence voluntarily, the wire is unnecessary. Bring the head into position and converge the eyes, giving attention to the diagram. It will be seen that the red and black lines are not quite parallel (or do not quite coincide), and that they are less nearly so as the convergence is increased. The red lines (seen by the left eye) seem to incline a little toward the right, and the black lines (seen by the right eye) toward the left. When the convergence is great, the horizontal lines also will show the rotation. This apparent rotation of the lines is not, as in the case of the after-image, a sign that the corresponding eye has rotated in the same way, but that it has rotated in the opposite way.

b. Repeat this with the head much inclined forward (the equivalent of elevating the eyes) and with it thrown far back (equivalent of depressing the eyes), taking care that the same degree of convergence is maintained. In the first case the apparent rotation of the lines is increased, and

in the second decreased to zero, or even transformed into rotation in the opposite direction.

Helmholtz, *A*, Fr. 609–610 (469–470); Le Conte, 177–191; Hering, *A*, 496 ff.; Aubert, *A*, 658 ff.

134. Involuntary Movements of the Eyes. Lay a small scrap of red paper on a large piece of blue. Fixate some point on the edge of the red. After a few seconds of steady fixation, the color near the line of separation will be seen to brighten, now in the red and now in the blue, thus betraying the small unintentional movements of the eyes.

Helmholtz, *A*, 539, Fr. 511 (389).

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FICK, A. E., AND GÜRBER: Ueber Erholung der Netzhaut, *v. Graefe's Archiv*, XXXVI., 1890, ii., 245–301. See also Hering's critique, Fick's reply, Hering's rejoinder, and Fick's second reply. *ibid.*, XXXVII. and XXXVIII.

VON FLEISCHL: Physiologisch-optische Notizen (2te Mittheilung), *Sitz.-ber. d. k. Akademie d. Wiss. i. Wien, math.-nat. Classe*, LXXXVI., 1882, *Abth.* iii., 8–25.

HELMHOLTZ: *A.* Handbuch der physiologischen Optik, 2te. Aufl., Hamburg und Leipzig, 1886–1892.

Of this second edition of Helmholtz's work but seven parts have so far appeared. The latest complete edition is the French translation by Javal and Klein (Optique physiologique, Paris, 1867). The references following the experiments are given when possible for both the second German edition and the translation. The figures in parentheses following those for the translation are the pages of the first German edition taken from the double paging of the French version. Having been taken thus at second hand, they may sometimes be in error by a page or

two, but it seemed better to run that risk than to omit them altogether. It is hardly necessary to add that this work is above all others the masterpiece of physiological and psychological optics.

B. Die Störung der Wahrnehmung kleinster Helligkeitsunterschiede durch das Eigenlicht der Netzhaut, *Zeitschrift für Psychologie*, I., 1890, 5–17.

HERING: *A.* Der Raumsinn und die Bewegungen des Auges, Hermann's Handbuch der Physiologie, III., Th. i., 343–601.

B. Beiträge zur Physiologie, Leipzig, 1861–64.

C. Ueber den Einfluss der Macula lutea auf spectrale Farbengleichungen, *Pflüger's Archiv*, LIV., 1893, 277–318.

HESS: Untersuchungen über die nach kurzdauernder Reizung des Sehorgans auftretenden Nachbilder, *Pflüger's Archiv*, XLIX., 1891, 190–208.

HEUSE: Zwei kleinere Mittheilungen aus dem Gebiete der physiologischen Optik, *v. Graefe's Archiv*, XXXIV., 1888, ii., 127–134.

HILLEBRAND: Ueber die specifische Helligkeit der Farben (mit Vorbemerkungen von E. Hering). *Sitz.-ber. d. k. Akademie d. Wiss. i. Wien, math.-nat. Classe*, XCVIII., 1889, Abth. iii., 70–120.

LAMANSKY: Bestimmung der Winkelgeschwindigkeit der Blickbewegung, respective Augenbewegung, *Pflüger's Archiv*, II., 1869, 418–422.

LAQUEUR: Ueber pseudentoptische Gesichtswahrnehmungen, *v. Graefe's Archiv*, XXXVI., 1890, i., 62–82. Contains historical references.

LE CONTE: Sight, New York, 1881.

MACH: *A.* and *B.*, works cited with same letters in bibliography of Chap. II.

MAXWELL: On Color-vision at Different Points of the Retina, *Report of the British Association*, 1870; or Maxwell's Scientific Papers, Cambridge, 1890, Vol. II., 230.

ROOD: On a probable means of rendering visible the Circulation in the Eye, *American Journal of Science*, 2d Ser., XXX., 1860, 264. Additional observations on the Circulation in the Eye, *ibid.*, 385.

SACHS: Ueber die specifische Lichtabsorption des gelben Fleckes der Netzhaut, *Pflüger's Archiv*, L., 1891, 574–586.

SCHWARZ: Ueber die Wirkung des constanten Stroms auf das normale Auge, *Archiv für Psychiatrie*, XXI., 1890, 588–617.

TREITEL: Ueber das Verhalten der normalen Adaptation, *v. Graefe's Archiv*, XXXIII., 1887, ii., 73–112.

TSCHERNING: Beiträge zur Dioptrik des Auges, *Zeitschrift für Psychologie*, III., 1892, 429–492.

TUMLIRZ: Ueber ein einfaches Verfahren, die Farbenzerstreuung des Auges direkt zu sehen, *Pflüger's Archiv*, XL., 1887, 394.

UHTHOFF: Ueber die kleinsten wahrnehmbaren Gesichtswinkel in den verschiedenen Teilen des Spektrums, *Zeitschrift für Psychologie*, I., 1890, 155–160. Contains bibliographical notices on *minimum visibile*.

WOLF: Ueber die Farbenzerstreuung im Auge, *Wiedemann's Annalen*, XXXIII., 1888, 548–554.

WUNDT: *A*. Work cited in bibliography of Chapter I.
B. Beiträge zur Theorie der Sinneswahrnehmung, Leipzig, 1862.

ZEHFUSS: Ueber Bewegungsnachbilder, *Wiedemann's Annalen*, IX., 1880, 672–676.

The works of Helmholtz and Aubert mentioned above contain full bibliographies for the earlier literature of all the subjects considered in this and the next two chapters.

CHAPTER VI.

Sensations of Light and Color.

THE aim of the following experiments is not to settle conflicting color theories, but rather to present the most important experimental facts which all color theories must take into account.[1] Authoritative statements of theories may be found as follows: Young-Helmholtz theory; Helmholtz, *A*, 344–350, Fr. 380–387, 424–425, 484 (290–294, 320–321, 367); *B*, 249–256. Hering's theory; Hering, *A*, 70–141; *M*, 76–79. Hering has not yet made a general statement of his theory in its later developments, and his present views must be gathered in more or less fragmentary condition from his numerous special articles. The theories of Helmholtz and Hering are the most prominent of current theories; and something on them, especially on the first, will be found in the physiologies generally, and in some works on color in the arts. Of other theories there are a considerable number; see, for some of them, von Kries; Wundt, *A*, and *B*; Donders, *A* and *B*; Christine Ladd Franklin, *A* and *B*; Ebbinghaus, *A*.

Most color theories attempt to simplify the multiplicity of ordinary color sensations by considering them as compounds of a small number of simple or primary sensations. The number of primary colors is different in different theories; red, green, and violet (or blue) are selected by

[1] For concise statements of these facts, see Wundt, *A*, 3te Aufl., I., 487, 501, 4te Aufl., I., 529; and Christine Ladd Franklin, *A*.

the supporters of the Young-Helmholtz theory; red, green, yellow, and blue by Hering, Mach, and others; while Wundt is indisposed to make any particular colors more original for sensation than the rest. The selection has generally been dictated by considerations of physics, or the results of introspective analysis of the sensations; but efforts have lately been made to settle the question by careful examination of the color-blind, and by calculations based upon careful experiments. On the first, see the literature on color-blindness below; on the second, see Helmholtz, *A*, 456 ff., *D*, and König und Dieterici, *A*. White is unquestionably a sensation, and Helmholtz and Hering agree in holding the same with reference to black; though Fick and some others disagree, regarding it rather as the absence of sensation.

A given color sensation may be changed in three ways: in *color-tone*, in *saturation*, and in *intensity*, or, to use Maxwell's terms, in *hue*, *tint*, and *shade*. Changes in *color-tone* are such as are experienced when the eye runs through the successive colors of the spectrum. Changes in *saturation* are such as are produced by the addition or subtraction of white; when much white light is added, the color is a little saturated. Changes in *intensity* are changes in the brightness of the color. Changes in saturation and in intensity, if excessive, involve some change of color-tone also. Hering's theory does not admit changes in the *intensity* of light and color sensations in any ordinary sense of the word. Colors that by others are said to be of low intensity are regarded by Hering and his school as mixed with a large proportion of black; similarly those of high intensity are mixed with much white. In Hering's theory the possible changes are then reduced to two; changes in color-tone and in saturation, the latter including admixtures of both white and black (Hillebrand; Hering, *A*, 51 ff.).

In this group of experiments it has seemed best to follow the better known terminology, though Hering's conception of the matter ought not to be disregarded.

LIGHT AND COLOR IN GENERAL.

135. Color-Blindness, Holmgren's Method. *a.* Spread the worsteds on a white cloth in good daylight. Pick out a pale green (i. e., a little saturated green) that leans neither toward the blue nor the yellow; lay it by itself and require the person under examination to pick out and lay beside it all other skeins that are colored like it, not confining himself, however, to exact matches, but taking somewhat darker and lighter shades also, so long as the difference is only in brightness and not in color-tone. Do not tell him to pick out "the greens" nor require him to use or understand color words in any way; simply require the sorting. If he makes errors, putting grays, light browns, salmons, or straws[1] with the green, he is color-blind; if he hesitates over the erroneous colors and has considerable difficulty, his color-vision is probably defective, but in a less degree.

b. If the experimentee makes errors, try him further to discover whether he is "red-blind" or "green-blind" by asking him to select the colors, including darker and lighter shades, that resemble a purple (magenta) skein. If he is red-blind, he will err by selecting blues or violets, or both; if he is green-blind, he will select green or gray, or both, and if he chooses any blues and violets, they will be the brightest shades. If he makes no errors in this case, after having made them in the previous case, his color-blindness is incomplete. Violet-blindness is rare. See also Ex. 141 *b*.

Complete certainty in the use of even such a simple

[1] It is difficult to give the tints accurately in words. The experimenter should consult the colored charts given in the works of Jeffries mentioned in the bibliography, and in Rayleigh, *B.*

method as this is not to be expected without a full study of it and experience in its application. Helmholtz, Hering, König, Kirschmann, and others give exact methods for determining the particular colors that are lacking in the vision of the color-blind.

On color-blindness and methods of testing for it, see Helmholtz, *A*, 357–372, 456–462; Fr. 388–399, (294–300, 847–848); Holmgren; Jeffries, *A* and *B*; Rayleigh, *A* and *B*; Hering, *H*, *I*, *N*, Hess, *B*; Abney, *A*; Abney and Festing; König, *B* and *C*; Brodhun, *A* and *B*; König und Brodhun; König und Dieterici, *A*; Schuster; Preyer; Donders, *C*; Kirschmann, *A*; Pole.

136. Vision with Peripheral Portions of the Retina: Perception of Light. A very faint light often appears brighter when its image lies not in the *fovea*, but a few degrees away from it. If no increase of brightness is observed, it is at least difficult to trace any decrease in brightness till the image is many degrees from the *fovea*. This experiment is most easily made at night with faint stars. In the laboratory it may be made with the dark box. On the rear wall of the box place in a horizontal line three bits of white paper of equal size, at such distances that the line of sight moves through an angle of ten degrees in turning from the middle one to either of the outer ones. Make a pin-hole above and below the middle piece, distant from it about an inch, and cover the holes on the outside with paper till the holes are barely visible after the eye has been some time adapted. These bright points serve to steady the eye. The eye should not, however, be directly fixed upon them, but at a point midway between them. Reduce the illumination of the box to a minimum (e. g., to the amount of light that would enter through a pin-hole covered with one or more pieces of porcelain or translucent cards), wrap the head and the end of the box in an opaque cloth, and allow the eyes to become adapted to the darkness,

looking from time to time for the shimmer of the papers at the back of the box. Full adaptation requires a long time, but fifteen minutes is sufficient in this case. By degrees, if the illumination is of the right intensity, the papers will be seen very faintly. If the eye is turned directly towards one of them, it often disappears in the retinal light while the others brighten. Fixate each of them successively, and compare its brightness with the others; fixate also other points in the field so as to bring the images upon different quadrants of the retina. Close the eyes from time to time to renew the adaptation, and avoid observations when the retinal light is strongly concentrated in the centre of the field.

On the results of such experiments as this, and on the explanation of the phenomenon observed, experimenters are somewhat at variance, but see Helmholtz, *A*, 268; Aubert, *A*, 495, *B*, 89 ff.; A. E. Fick, *B*; Kirschmann, *B*; Treitel, and the literature cited by them.

137. Vision with Peripheral Portions of the Retina: Perception of Color. The distribution of the sensibility of the retina for color is unlike that for light. At the very centre the pigment of the yellow spot itself interferes somewhat with the correct perception of mixed colors (see Ex. 115). In a zone immediately surrounding this all colors can be recognized. Outside of this again is a second zone in which blue and yellow alone can be distinguished, and at the outermost parts not even these, all colors appearing black, white, or gray. The zones are not sharply bounded, but blend into one another, their limits depending on the intensity and area of the colors used. The fixing of the boundaries of the zones of sensibility is known as perimetry or campimetry.

a. With the apparatus at hand, find at what angles from the centre of vision on the vertical and horizontal meridians

of the eye the four principal colors, red, yellow, green, and blue, can be recognized; try white also. Keep the eye steadily fixed on the fixation mark of the instrument, and have an assistant slide the color (say a bit of colored paper 5 mm. square pasted near the end of a strip of black cardboard an inch wide) slowly into the field from the outside. It will be well to move the paper slowly to and fro at right angles to the meridian on which the test is made, so as to avoid retinal fatigue. Take a record of the point at which the color can first be recognized with certainty. Repeat several times and average the results. The size of the colored spot shown should be constant for the different colors, and the background (preferably black) against which the colors are seen should remain the same in all the experiments.

b. Repeat the tests with colored squares 20 mm. on the side, and notice the earlier recognition of their color as they approach from the periphery.

c. Try bringing slowly into the field (best from the nasal side) bits of paper of various colors, especially violet, purple, orange, greenish yellow, and greenish blue; or better, hold the bit of paper somewhat on the nasal side of the field and turn the eye slowly toward it, beginning at a considerable angle from it. If the paper is held before a background containing a line along which the eye can approach the paper, the eye will be assisted in making the approach gradual; the apparatus used in Ex. 113 *b* can easily be adapted for this purpose. Observe that on the outer parts of the retina these colors first get their yellow or blue components, and only later the red or green. If the range of choice is sufficiently large, it may be possible to find a red (inclined toward red-purple) and a green (inclined toward the blue), which, like pure blue and yellow, change only in saturation and not at all in color-tone as they move inward

toward the centre of the field. These four colors are the *Urfarben* or primary colors of Hering.

Helmholtz, *A*, 372–374, Fr. 399–400; Hess, *A*; Hering, *G*, *L*; A. Fick, *A*, *B*, 206 ff.; A. E. Fick, *B*, 479 ff.; Aubert, *A*, 539–546, *B*, 116 ff.; Kirschmann, *C*.

138. Changes in Color-Tone. In the spectrum, change of wave-length, if not too small, is accompanied by change of color-tone. The change is most rapid in the yellow-green and blue-green regions of the spectrum, less rapid toward the ends, and at the extreme ends the only changes are those in brightness. With the spectroscope and daylight find the characteristic Fraunhofer lines *D*, *E*, *F*, *G*, and *H*. The *D* line lies in the golden yellow, *F* in the greenish blue, and *H* at the end of the violet. Between *D* and *F* the wave-length changes from 589.2 to 486.1 $\mu\mu$ (from 5.092×10^{14} to 6.172×10^{14} vibrations per second), and the color runs through yellow and green to blue, while from *F* to *H* with the nearly proportional change in wave-length from 486.1 to 393.3 $\mu\mu$ (from 6.172×10^{14} to 7.628×10^{14} vibrations per second) the change is only from greenish blue to violet. Notice the region from near the line *G* to the end of the spectrum which shows little change in color-tone and a similar region of uniform color-tone at the red end. Notice also the tendency of the succession of spectral colors to return upon itself, shown in the resemblance of the violet and red.

Helmholtz, *A*, 289, 320, Fr. 319 (237); Wundt, 3te Aufl., I., 449 f., 4te Aufl., I., 485 f.; A. Fick, *B*; Aubert, *A*, 530 f. On just observable changes in color-tone, see B. O. Peirce, Jr., König und Dieterici, *B*, Brodhun, *A*, and the literature there cited.

139. Changes in Saturation. These are easily shown on the color-mixer. Make a succession of mixtures of red and white, beginning with a proportion of white that just changes the red, and increase the proportion till no effect of red remains. At first use a small disk of red laid on

over the larger disks as a sample with which to compare the mixtures. Toward the end of the experiment exchange the red for a small white disk. Notice the changes of color-tone that are to be observed, especially when the amount of color is small. Try similarly with the other chief colors. According to Rood, who worked with the color-mixer, yellow-green and violet are unchanged; Helmholtz's results with spectral colors are somewhat different.

Changes in saturation can also be made by adding gray of any shade instead of white. The whole range of mixtures can be shown on a single disk, like that in Ex. 141, by painting the star upon a white or gray ground, or by pasting a star of colored paper on such a ground. With white, however, the rays of the star must be given a leaf shape, or the color will fall off too rapidly from the centre.

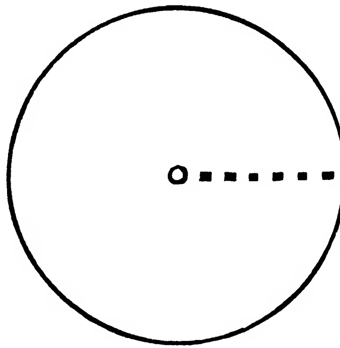
Helmholtz, *A*, 322, 470–471, Fr. 369 (281); Aubert, *A*, 531–532; Rood, *A*, 39–40, 194–201; Nichols, *A*.

140. Changes in Intensity: Black and White. Black and white are the extremes of intensity in the series of grays. The ordinary black and white of conversation are, however, considerably short of these extremes.

a. Compare a bit of black velvet or of black cardboard with a still deeper black by holding it in front of the opening in the dark box. Compare, also, ordinary white paper in diffused light with the same in direct sunlight, or with a brightly illuminated white cloud.

b. Just observable differences with medium intensities. Prepare a disk like that shown in the accompanying cut by drawing along a radius of a white disk a succession of short black lines of equal breadth. Let the breadth of the line correspond to about one degree on the edge of the disk. Since the breadth of the line is everywhere the same, it will occupy a relatively greater angle as it nears the centre.

When the disk is set in rapid rotation, each short line will give a faint gray ring, those at the outer edge being very faint, those nearer the centre, darker. Find which is the faintest ring that can be seen, and calculate the proportions of black and white in it.[1] The ratio of black to white measures approximately the just observable decrease in intensity below the general brightness of the disk. The results of Helmholtz and Aubert are respectively: Helmholtz, 1 : 117 to 1 : 167, Aubert, 1 : 102 to 1 : 186, the differences depending on the intensity of the general illumination of the disk. Some wandering of the eyes is helpful, but too rapid motions which tend to break up the even gray of the rings must be avoided. It is absolutely essential that the rotation be very rapid and perfectly free from vibration — so rapid that with moderate motions of the eyes the uniform gray of the rings is not disturbed. If great rapidity is impossible, replace the single black line by two of proportionately less breadth on opposite sides of the disk, or by four at 90°.



e. With these very faint rings a disappearance and reappearance is to be observed somewhat like that found for

[1] The formula for the amount of black, assuming that the radial line is absolutely black, and taking some arbitrary point, *e.g.*, the middle, for calculation, is of course $\frac{b}{2\pi r}$, where b is the breadth of the radial line, and r the distance of the chosen point from the centre of the disk. The black of the lines is not quite absolute, even when the blackest black paint is used. The differences in sensation are therefore smaller than those shown by the calculation.

just audible sounds in Ex. 61 *b*. The observation is most conveniently made, according to Pace, on a disk of the following dimensions : diameter of disk, 20 cm., width of radial line, 5 mm., length of the short lines, 5 mm., spaces between the short lines, 8 mm., distance of innermost short line from the centre of the disk, 17 mm.

Helmholtz, *A*, 384-393; Fr. 411–419 (310-316); Aubert, *A*, 487-492; on *c*, Pace. For references on the just observable difference of intensity with different standard intensities, see the chapter on Weber's Law below.

141. Changes in Intensity : Colors. At their maximum intensity all colors tend toward white or yellowish white. Red, however, hardly gets beyond the yellow ; green becomes first yellow, then white, while blue and violet easily reach it. At their minimum intensity all colors appear gray or black.

a. The maximum intensity may be observed with spectral colors, though not entirely homogeneous ones, with a prism placed in the sunlight so that it throws an extended spectrum on the wall. Hold a card, pierced with a pin-hole, before the eye, and bring the eye successively into the different colors, looking meanwhile at the prism. Something of the same kind may be seen by looking through pieces of colored glass at the disk of the sun behind a cloud (in which case the portions of the cloud seen at the sides of the glass afford a means of comparison), or at the image of the sun reflected from an unsilvered glass plate, or by concentrating light from colored glass on white paper with a convex lens.

b. The minimum intensity with spectral colors may be observed with a spectroscope. Adjust the instrument so that the chief Fraunhofer lines can be seen, and then place, as a source of light, at a little distance from the slit of the instrument, a screen covered with dark gray paper or black velvet. Though no color remains, a little light can be made

out — brightest in the region before occupied by the green. The observer must envelop his head and the ocular of the instrument in an opaque cloth, and allow time for the adaptation of his eye. This colorless spectrum probably represents what is seen by a totally color-blind eye.

Von Bezold, with whom this experiment originates, observed with gradually decreasing intensity a falling out of the yellows and blues before the final stage of colorlessness was reached. König doubts whether the red ever loses its color entirely.

With pigment colors a convenient way is to paste equal squares of colored papers upon a piece of cardboard, and then to place the whole in the dark box, and gradually reduce the illumination, or starting with the illumination at zero, gradually increase it. Try with both black and white cardboard as background. For demonstrational purposes a disk like that in the accompanying cut (in which the shaded part stands for color, and the solid black for black) may be used and the whole series of intensities shown at once.[1]

Helmholtz, *A*, 402–444; A. Fick, *B*, 200–202; Aubert, *A*, 532–536; Rood, *A*, 181–194; C. S. Peirce. On *a*, Helmholtz, *A*, 284–285, 465–466, Fr. 315 (234); Brodhun, *B*. On *b*, Helmholtz, *A*, 469, 471–

[1] Since the black of the disk is really a very dark gray, and would thus make a change in saturation, this is not an absolutely pure experiment, but is sufficiently exact for showing the general effect of darkening. If a practically perfect black is desired, it may be had, following Rood, by making the colored star rotate before an opening into a dark room or a suitable dark box.

472; von Bezold, *A*; Ebert; Abney and Festing; König, *A*, 354 ff., where other literature is cited.

For measurements of the just observable difference of intensity for different colors, see Helmholtz, *A*, 402–415; Aubert, *A*, 531; A. Fick, *A*, 177; and the references given by them.

142. Purkinje's Phenomenon. In a light of moderate brightness choose a bit of red paper and a bit of blue paper that are of about equal intensity and saturation, carry both into full sunlight and notice which appears brightest; carry both into a darkened room, or place them in the dark box and compare them again. If a dark room or box is not at hand, observe them through a fine pin-hole in a card, or even with nearly closed eyes.

Helmholtz, *A*, 428–430, 443–444, Fr. 420–425 (317–321); Hillebrand; König, *A*; Charpentier, *A*, 227 ff., 335 ff.; Rood, *A*, 189 ff.

143. Size of the Colored Field. When the retinal area stimulated is very small, colored surfaces appear colorless, with ordinary intensities of illumination. When somewhat larger they may appear colored, but not necessarily in their true color-tone. The background against which they are placed is also important.

a. On pieces of black and white cardboard, paste small squares of several kinds of colored paper, one series 5 mm. square, one 2 mm. square, and one 1 mm. square. Walk backward from them and notice their loss of color. Observe also the changes in color-tone.

b. A number of retinal impressions, even when not contiguous, are mutually supportive in color effect. This is conveniently shown in the indirect field. In a two-inch square of black cardboard, punch sixteen holes arranged in the form of a square, four rows of four holes each. The holes should be an eighth or three-sixteenths of an inch in diameter, and be separated by spaces of the same extent. Paste upon the back of the square a piece of red paper of

sufficient size to cover the holes, thus making of them sixteen little red circles. Prepare also another piece of black cardboard of such shape that it may be laid over the square and cover all the holes except one of the corner ones, and again when necessary may easily be removed.

With the apparatus used in Ex. 137, find the point on the nasal half of the retinal horizon where the single red circle can just no longer be seen in its true color. In making this determination, the square should be so held that the diagonal to which the uncovered circle belongs is horizontal. When the point has been found, uncover the remaining fifteen circles (all farther toward the periphery), and notice that the color of the group can be seen distinctly. Fatigue in fixing the limit at which the circle can be seen should be avoided.

On *a*, Helmholtz, *A*, 374–375, Fr. 399–400 (300); Aubert, *A*, 536–539; Hering, R, 18. On *b*, A. E. Fick, *A* and *B* (especially 451–452).

144. Duration of Illumination. Fechner's Colors. The retinal inertia is different for different colors. In the experiments on after-images (Ex. 125 *d*), it was observed that the after-image of a white surface faded away through a succession of colors; a succession of colors appears also to result from a very brief vision of a white surface. This can be seen upon almost any slowly rotating disk of black and white; those used in Exs. 128 *b* and 145 *c* show the colors well, and that in Ex. 145 *a* shows something of the dependence of particular colors upon particular rates of recurrence. Rotate any of these disks with less rapidity than that required for a uniform gray, and, keeping the eyes steadily fixed upon some point of its surface, notice both the advancing and the retreating edges of the white portions of the disk. The colors may not appear instantly, but are not difficult to get with attentive gazing.

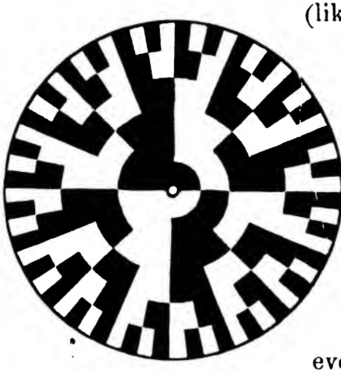
Very striking and beautiful effects can be obtained by

substituting for the black and white disk a black one from which narrow sectors have been removed. This pierced disk is rotated before a brightly lighted background, e. g., a sheet of white cardboard in full sunlight, a bright cloud, or the clear sky, and the eye is brought very close to the disk.

Helmholtz, *A*, 530–533, Fr. 500–504 (380–383); Fechner, *A*; Brücke; Exner; Aubert, *A*, 560; Rood, *A*, 92 ff., *B*; Nichols, *B*; Charpentier, *B* and *C*.

145. Rate of Rotation Required for a Uniform Blending of Black and White. All blending of colors by rotation depends on the phenomenon of positive after-images (Ex. 125). A disturbance once set up in the retina does not at once subside, but continues an instant after the removal of the stimulus. If stimuli follow in sufficiently rapid succession the disturbances fuse, and the result is the same as if the stimuli had been mixed before reaching the retina. A rough determination of the rate required for uniform blending may be made with the color-mixer and a metronome.

a. Place the color-mixer in such a position that the disk (like that in the margin) shall be illuminated by diffused daylight only. Turn the driving-wheel slowly and ascertain, by counting, how many turns of the disk correspond to one turn of the driving-wheel. Start the metronome, and turn the driving-wheel in time to its beats, making a turn every one, two or four beats.

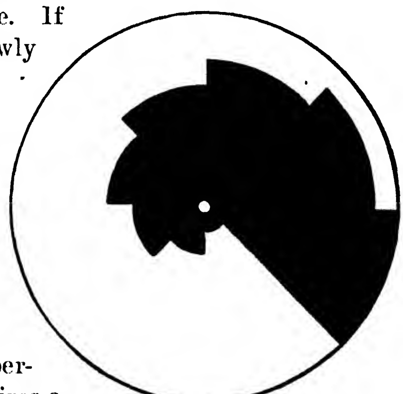


Notice which of the rings, if any, is just blended into a uniform gray. If none is just blended, change the rate of

the metronome a little, and repeat the trial till such a one is found. From the rate of the metronome, the number of turns of the driving-wheel, and the number of white sectors in the just blended ring, find the number of stimuli per second required. The experiment is easier when two observers work together, one giving his attention to the regular driving of the color-mixer, and the other to watching the disk. The driving-belt of the instrument must be tight enough not to slip, and the metronome should be kept well wound up. Its scale should also be verified by counting with a watch. The observer must of course avoid eye motions which break up the uniformity of the gray.

b. Repeat the determination with the disk in direct sunlight; also in a partially darkened room or at twilight.

c. A disk like that in the margin shows mixtures of several different proportions of black and white at once. If such a disk is brought slowly to the rate just necessary to give a uniform gray at the centre, a little flickering can still be traced in the outer rings. Care should be taken not to fixate the middle of the disk exclusively, for with moderate illumination the periphery of the retina requires a little greater speed for uniform blending than the centre.



Helmholtz states that little difference is to be observed in the rate at which the flicke ing ceases with the somewhat similar disk shown at the left in

Ex. 152 *d*, but with that given here, it is believed that careful observation will not fail to show a difference.

Helmholtz, *A*, 488 ff., Fr. 453 (344) ff.; Aubert, *A*, 517; A. Fick, *B*, 211–222; Nichols, *B*; Bellarminow and the literature cited by him.

146. The Talbot-Plateau Law. This law may be stated as follows: When once the rate of rotation is sufficient to give a uniform sensation, the color and brightness of any given concentric ring of the disk are the same that they would be if all the light reflected from it were evenly distributed over its surface, and no further increase in rapidity produces any effect upon its appearance. Rotate the disk used in Ex. 145 *a*, and increase the rapidity till the innermost portion gives a uniform gray. When this appears, the rate of recurrence in the outermost ring is 32 times more rapid than in the innermost, and yet no difference in shade is to be seen. To show that the gray is actually of the same brightness that would come from an even distribution of the light reflected from the whole surface of the ring, prepare a disk with many equal black and white sectors — 32 or more of each. Place the disk on the color-mixer, and look at it when at rest through a double convex lens of short focus (e.g., 1 in.), held at such a distance from the eye and disk that no distinct image is formed, but the field of the lens appears an even blur of gray. Now put the disk in rapid rotation and notice that the gray remains unchanged.

The result of these experiments would be the same were other colors substituted for black and white.

Helmholtz, *A*, 482–485, Fr. 446–450 (338–341); Aubert, *A*, 515–516; Talbot; Plateau.

147. Brücke's Experiment. When the rate of rotation is insufficient to produce an even blending, the brightness

of the disk is influenced by the rate. Set the disk used in Ex. 145 *a* in rapid enough rotation to blend the innermost ring, and then let it gradually come to rest. As it turns more and more slowly, there will be observed in one ring after another, beginning with the innermost, just as it loses its uniform character, a notable brightening. The white sectors now have opportunity to produce their full effect upon the retina before they are succeeded and their impression cut off by the black sectors.

Helmholtz, *A*, Fr. 455–456; Exner; Aubert, *A*, 510.

COLOR MIXING.

148. Mixed Colors. Experiments upon this subject cannot be regarded as entirely satisfactory except when made with pure (homogeneous) spectral colors. The colored papers with which the following experiments are made show anything but homogeneous colors, as can easily be seen by looking at scraps of them on a dark background through a prism. They produce the same mixture effects, however, that spectral colors of the same tone, intensity, and saturation would produce; and the great facility of their manipulation on the color-mixer recommends them for preliminary experiments and for illustrative purposes.

Three colors properly selected serve to produce by their mixtures all the intermediate colors (though in most cases in less saturation) with purple and white (i. e., gray) in addition. The colors generally selected are red, green, and blue or violet. Green cannot be mixed from colors that themselves do not resemble it; i.e., it can be mixed from yellow-green and blue-green, but not from yellow and blue, and not in anything like full saturation.

The general facts of color mixing, together with the method of representing them in a two dimensional diagram, were first discovered by Newton, and are sometimes desig-

nated by the general term of Newton's Law. For the methods of constructing such diagrams, see, among others, Helmholtz, *A*, 334 ff., Aubert, *A*, 524 ff., and Rood, *A*, 218 ff., 224 ff.

a. Mix a yellow from red and green on the color-mixer. The yellow produced will be dark, and, as a test of its hue, should be matched with a mixture of yellow and black made with smaller disks set on above the first. In the same way mix a blue from green and violet that shall match a mixture of blue and black (or blue, black, and white).

b. From red and violet or blue, mix several purples between violet and red.

c. From red, green, and violet, mix a gray that shall match a mixture of black and white on the small disk. In such a case as this it is highly probable that the gray appears, because the combined colors furnish among them light of all wave-lengths in about the proportions in which they occur in ordinary white light. With the homogeneous red, green, and violet of the spectrum, the case would of course be different. To avoid troublesome after-images, the adjustment of the disks should be left to an assistant, or the observer should wear dark glasses, except when the disks are in revolution at full speed.

If the colored disks used in these experiments are not opaque, several should be used at once instead of a single one.

For demonstrational purposes mixtures of two colors in different proportions can be shown on a single disk of the star form (see Ex. 141) by painting the star in one color and the ground of the disk in another (or by pasting colored papers instead of painting), but in either case some trial will be necessary to determine the proper shape for the rays.

Helmholtz, *A*, 311–316, 320–322, 325–333, 375, 376–473, 485, Fr. 359–365, 367–369, 450 (272–277, 279–281, 341); Aubert, *A*, 521–524; Hering, *M*; Maxwell, *A* and *B*; Rood, *A*, 124 ff.

149. Complementary Colors. The combination of red, green, and violet mentioned in the last experiment is not the only combination that gives white or gray. For every color there is another or complementary color, which, mixed with it, gives a colorless combination. Some of these pairs are red and blue-green, yellow and indigo-blue, green and purple, blue and orange, violet and yellow-green.

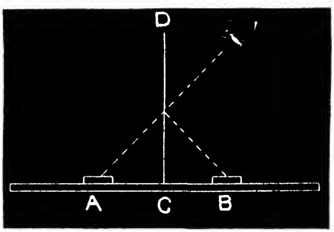
a. Try several of these pairs upon the color-mixer, matching the resultant gray with a mixture of black and white on the small disk. It will probably be found in some cases that no possible proportions of the colored papers at hand will give a pure gray. In that case a little of the color complementary to that remaining in the gray must be added. Suppose the red and blue-green papers, when combined, give gray with a tinge of brown (i.e., dark orange); a certain amount of blue must then be added to compensate. For example, with certain papers 180° of blue-green + 36° indigo-blue + 144° red make a gray that matches 90° white + 270° black. To see the true complement of the red used, it is then necessary to prepare a disk carrying green and indigo in the proportions of 180 and 36; i.e., 300° blue-green, 60° indigo. In the same way the complement of the blue-green used is a bluer red than that of the red paper, and may be seen by itself by mixing 288° red with 72° indigo. It is very important here, and in all cases where a resultant white or gray is to be observed, to have some undoubted white or gray in the field to prevent mistake in very faint tinges of color.

The criticism made upon Ex. 148 *c* applies here with equal force. To be conclusive, the experiment must be made with far simpler colors than those of colored papers.

b. Negative after-images, when projected on a white surface, are seen in colors approximately complementary to those that give rise to the after-images. Compare complementary colors found in this way with those found on the color-mixer.

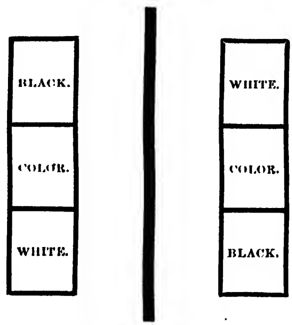
Helmholtz, *A*, 316–319, Fr. 365–367 (277–278); Aubert, *A*, 521-524; König und Dieterici, *A*, 284 ff.; Rood, *A*, 161 ff.

150. Other Methods of Mixing Colored Lights. *a.* Lambert's Method. The Reflection Color-Mixer. This is the simplest of all the methods. The colors to be mixed are placed on a suitable background (e. g., a smooth surface of black velvet), on opposite sides of a vertical glass plate. The eye is brought into such a position that the reflected image of the color on one side appears to overlie that seen by transmission on the other side. The glass must of course be of good quality and clean. The relative intensity of the colors can be varied by varying their distance from the glass. Bringing the colors near the glass, or raising the eye, strengthens the reflected and weakens the transmitted light. Strips of colored paper placed with their ends next the glass, provided the illumination is equal, will show an even blending of the colors through a considerable range of intensities, one color predominating at one end of the combined image, the other at the other end.



By substituting a bit of glass on a black background for one of the colors, and then placing the instrument so that a portion of clear sky may be reflected in the glass, it is possible to mix sky-blue with its complement, or with any other color.

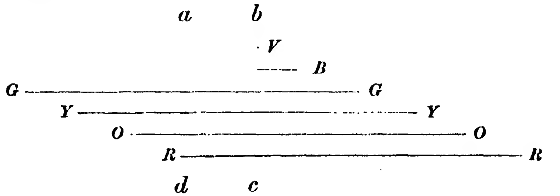
To mix two colors in equal proportions, arrange them with black and white, as in the diagram below. Adjust the glass (or the position of the eye) till the grays made by the black and white at the ends exactly match; the colors will then be mixed in equal proportions.



b. Mixture by Double Refraction. Colored areas placed side by side appear mixed when regarded through a double refracting prism. The prism doubles both fields, and causes a partial overlapping. In the overlapped portion the colors are mixed, each color being present in the mixture at approximately half its original brightness. The prism should be achromatic.

c. Mixture of Spectral Colors. Fine mixtures may be obtained with a prism and Figs. 1, 2, and 3 of Plate I.; or, still better, from figures shaped like these, but in white upon a black ground. Since a prism refracts different kinds of light in different degrees, it produces a multitude of partially overlapping images of a bright object, which appear to the eye as colored fringes. (Observe through a prism held horizontally, an inch square of white paper on a black background.) These overlapping images may be illustrated by the following diagram, in which the horizontal lines stand for the

images, and the capital letters for the colors of the light producing them.



In the area *a b c d* all the images overlap and the white of the paper is still seen. Toward the left from *a*, however, the different kinds of light gradually fail, beginning with the red. The successive colors from greenish blue to violet result from the mixture of what remains. At the other end a similar falling away of the colors gives the succession from greenish yellow to red. In Fig. 1, the spectra seen on the upper and lower edges of the inch square of white paper are brought side by side; on one side red, orange, and yellow, and on the other greenish blue, blue, and violet. The colors that stand side by side are complementary pairs, both in tone, intensity, and saturation; for the greenish blue is the white of the paper less the red, and the blue the same less the red, orange, and yellow, and so with the rest; and if the two spectra be exactly superposed, as can be done with an adaptation of the method of *b* above, they will make precisely the white from which they originated.

If a very narrow strip of white upon a black ground is looked at through the prism, the images overlap less and another color appears; namely, green, as may be seen in Fig. 2 on the narrow white band between the black bars. When, on the other hand, a narrow black band on a white ground is taken, the spectrum of the white surface above and of that below partially overlap, and give another set of mixtures. If the diagram is held near the prism at first, and

then gradually withdrawn from it, the advance and mixing of the spectra can easily be followed. Besides the greenish yellow at one end and the greenish blue at the other, there are a rich purple, complementary to the green beside it, and a white between the purple and the greenish yellow. The last is a white produced by the mixture of the blue of one spectrum with the complementary orange-yellow of the other.

Fig. 3 shows a number of color mixtures with different proportions of the constituents. In the spectra from the white triangle appear mixtures of each color in the spectrum seen on the white band in Fig. 2, with every other color found there. Upon the black triangle the spectra from the white edges above and below show mixtures similar to those on the black band in Fig. 2. The diagram should be placed at such a distance that a little of the white and black triangles can still be seen.

Helmholtz, *A*, 350–357, 485, 491–493, Fr. 402–407, 450, 458–461 (303–306, 341, 347–349); Aubert, *A*, 521–524; Maxwell, *A*; Rood, *A*, 108 ff., 124 ff.; Hering, *O*; von Bezold, *B*, 77 ff. On *a* and *c*, Benson. On refined methods of mixing spectral colors, see especially the first reference to Helmholtz.

CONTRAST.

The effect of one color on another, when not mixed with it, but presented to the eye successively, or simultaneously in adjacent fields, is known as contrast. Two kinds are distinguished, *Successive contrast* and *Simultaneous contrast.* The color that is changed or caused to appear upon a colorless surface, is known as the *induced color;* the color that causes the change is called the *inducing color.* Successive contrast is largely a matter of negative after-images, and their projection upon different backgrounds, and is universally regarded as a matter of physiology. Simultaneous contrast, on the contrary, has been regarded by Helmholtz and his

supporters as a matter of psychology, as a sort of misjudgment. The studies of the last few years, however, chiefly those of Hering, have demonstrated that simultaneous contrast also in most, and probably in all cases, is physiological, a phenomenon of the retina (and its central connections), not of mistaken inference.

151. Successive Contrast. *a.* Prepare a set of colored fields of the principal colors, including white, black, and gray, say 3 x 5 inches in size, and some small bits of the same colors, say 1 cm. square. Lay a small square on the black field, get a strong negative after-image, and project it first on the white and then on the other fields. Notice that the color of the after-image spot is that of the field on which it is projected, minus the color that produced the spot; e. g., the after-image of red projected on violet looks blue, and on orange looks yellow. Or, to say the same thing in other words, the color of the spot is a mixture of the color of the after-image with the color of the ground upon which it is projected. Thus a blue-green after-image when projected on violet, gives blue; when projected on orange, gives yellow. Notice that when the image is projected on a field of the inducing color it causes the spot on which it rests to look dull and faded; but when it is projected upon a field of complementary color, it makes the spot richer and more saturated. Indeed, it is only by first fatiguing the eye for one color and then looking at its complement that the most saturated color sensations can be produced. In general, colors that are complementary, or nearly so, are helped in appearance by contrast; those that resemble each other more nearly are injured.

b. These effects, in even greater brilliancy, can be seen by laying the small square of color directly on the larger colored surface, staring at it a few seconds, and then suddenly puffing it away with the breath. See also Ex. 134.

c. This contrast effect may be so strong as actually to overcome a moderately strong objective color. Place a small piece of opaque orange paper in the middle of a pane of red glass and look through the glass at a clear sky or bright cloud. The strength of the induced blue-green will be sufficient to make the orange seem blue. See also Ex. 124 *d.*

Helmholtz, *A*, 537–542, Fr. 510–515 (388–392); Hess, *C*; Rood, *A*, 235 ff.

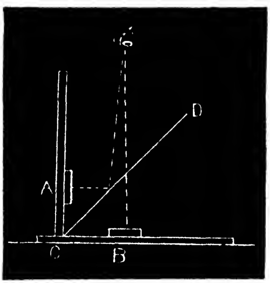
152. Mixed Contrasts. When special precautions are not taken to exclude successive contrast, both successive and simultaneous co-operate in the general effect. Some of the results are striking and beautiful.

a. Colored Shadows. Arrange two lights so that they shall cast a double shadow of a pencil or small rod upon a white surface. The daylight will answer for one light if it is not too strong, but it must not be forgotten that unless the light comes from an overcast sky it will be blue. Introduce different colored glasses one after another before one of the lights, and notice the beautiful complementary color that immediately appears in the shadow belonging to that light. The brightness of the two lights should be so regulated that the shadows shall be about equally dark when the colored glass is introduced before one of the lights. See also Ex. 155.

Use a blue glass, and adjust the relative intensities of the lights so that the yellow shadow appears at its brightest, and notice that it seems as bright as the surrounding blue, or even brighter. As a matter of fact, however, it receives less light than the surrounding portions; for in order to be a shadow, it must be a portion of the field from which the light is partly cut off.

b. Mirror Contrasts. Ragona Scinà's Experiment. Place upon the horizontal and vertical surfaces of the instrument

white cards carrying black diagrams.[1] The diagrams being in place, hold between the two at an angle of 45° a pane of colored glass, say green, and observe that the black of the horizontal diagram seems tinged with the complementary color, that is, purple. This contrast color may often be improved by slightly altering the inclination of the glass, or by changing the relative illumination of the diagrams by interposing a colorless screen between one or the other of them and the source of light, or by shifting the whole instrument. This experiment will be readily understood after a consideration of the accompanying cut. The glass plate is represented by *C D*, the black portion of the vertical diagram by the projection opposite *A*, that of the horizontal diagram by the projection at *B*. The light reaching the eye from the white portion of the horizontal diagram is colored green by the glass; that from the white portion of the vertical diagram is reflected from the upper surface of the plate, and is therefore uncolored.[2] The mixture of the two gives a light green field. For simplicity, we may assume that no light comes from the black portions of the diagram. Then in the portion of the light green



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[1] Any black spot will answer. For this experiment diagrams made up of sets of heavy concentric black rings, lines a quarter of an inch wide, separated by white rings of triple width, give an excellent effect. The diameters should be so chosen that a black ring on the horizontal diagram shall correspond to a white one on the vertical and *vice versa*, and shall appear to lie in the midst of the white when the diagrams are combined in the way described above. A pair of diagrams made up of parallel black bars, a quarter of an inch wide, separated by quarter inch spaces, and so placed in the instrument that they give a checker-board pattern when combined, are useful for keeping in the field a true black with which the changed colors can be compared.

[2] As a matter of fact, a small portion is also reflected from the lower surface of the glass, and contributes a minute amount of green.

field corresponding to the black of the vertical diagram, the white component will be wanting and the green will appear undiluted; in the portion corresponding to the black of the horizontal diagram, the green component will be wanting and the faint white (i. e., gray) should appear by itself. It does not, however, because of the contrast color induced upon it. As a matter of fact, the black portions are not absolutely black; the small amount of light that comes from them tends on one hand to make the green image (image of the black of the vertical diagram) a little whiter, and on the other hand to counteract the contrast in the purple image by adding to it a little green. Try the experiment with other glasses than green.

Another form of the mirror contrast experiment is as follows. Place a mirror where the sky or a white surface of some kind will be seen reflected in it. Lay upon its surface a plate of colored glass (green for example), and hold a little way above it a narrow strip of black cardboard or a pencil. Two images will be seen: one a vivid green, the other a complementary purple. The green image belongs to the surface reflection of the colored glass, as may be proved by observing that when the strip of cardboard touches the surface, the green image touches it also. The purple image belongs to the reflection from the back of the mirror. It is easy, by substituting a gray strip for the black, to show that contrast can suppress a weaker objective color actually present.[1]

e. Meyer's Experiment. Lay on a large colored field a small piece of gray or even black paper (e.g., 1 cm. wide by 2 cm. long), and cover the whole with a piece of semi-transparent white paper of the same size as the colored field. The contrast color will appear on the gray paper.

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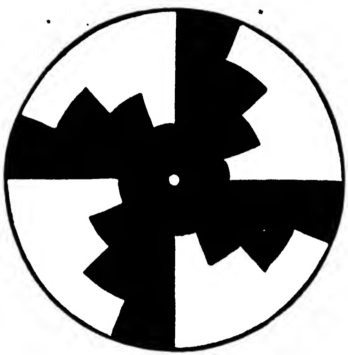
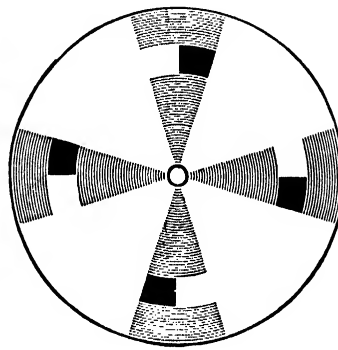
[1] For fuller explanation with diagram, see *American Journal of Psychology*, V., 1892-93, 407, and von Bezold, 154 f.

If thin tissue paper is used, more than one thickness may be needed for the best result. Paper mats, woven one way of gray paper and the other of colored, show this contrast beautifully. They may easily be made from kindergarten materials.

d. Mixed Contrasts with the Color-mixer. Disks made on the pattern of the cut at the left show beautiful contrasting





grays. The disk used in Ex. 145 *c* shows a longer series, but requires a more rapid rate of rotation. The same can be shown also by laying a number of small sheets of tissue paper over one another in such a way that they partially overlap, making a portion where there is but a single thickness, and next it a portion where there are two thicknesses, and next that again one of three thicknesses, and so on. When the whole is held up to the light, the contrasts of adjacent portions are very easily seen.

Contrast colors can be shown finely with disks like that in the cut at the right, in which the shaded portions represent color, the black portions, black, and the white, white. A little care is necessary in fixing the proportions of the color to white and black in the disks, but in general the

brightness of the gray should be about that of the color. When the contrast color has been satisfactorily obtained, bring near it a piece of white cardboard (e.g., 3 x 5 in.), so held with reference to the source of light that it appears about as bright as the contrast ring. Hold the card so that its shadow does not fall on the disk, or at least is out of sight. Notice the retreat of the contrast color from its edges. On such experiments as this much stress is laid by Helmholtz and the supporters of the psychological explanation of contrast.

Contrasts with two colors at once can be shown by making the inner portion of the colored sectors of one color, the outer portion of another. A temporary disk for showing contrast effects may be arranged by putting on the spindle of the color-mixer first a large colored disk (e.g., 20 cm. in diameter), then smaller combined disks of black and white (e.g., 12 cm. in diameter), and finally a still smaller colored disk (e.g., 10 cm. in diameter).

Helmholtz, *A*, 542 ff., Fr. 515–546 (392–417); Hering, *E*; Aubert, 496 ff., 546 ff.; von Bezold, 144–171; Rood, 241–272; Mayer.

For particular experiments, see the following: on *a* (second part), von Bezold, *B*, 153–154; on *b* (second part), Dove; on *c*, Meyer.

For quantitative measurements of contrast in grays, see Ebbinghaus, *B*; Lehmann; and Kirschmann, *D*.

153. Some of the Conditions that Influence Contrast.

a. Contrasts are stronger when the colors are near together. Lay a bit of white paper on a black surface, e.g., a piece of black velvet, and notice that the paper is whiter and the velvet blacker near the margin of the paper than elsewhere, notwithstanding that the eye moves about freely. This has received the name of "Marginal contrast" (*Randcontrast*).

On a piece of gray paper, the size of a letter-sheet, lay two strips of colored paper close side by side (e.g., pieces of

red and yellow or of green and blue, 1 cm. wide by 4 cm. long). Below them to the right and left, as far apart as the paper will permit, lay two other strips of the same size and color, red on the red side of the former pair, yellow on the yellow side. Notice the effect of the difference in distance on the contrasting pairs. Contrast of this sort is at a maximum when one color entirely surrounds the other.

b. Effect of size. When the area of the inducing color is large and that of the induced color is small, the contrast is shown chiefly on the latter; when the two areas are of about equal size, as in *a* above, the effect is mutual. Try with large and small bits of paper upon a colored field.

c. Borders and lines of demarcation that separate the contrasting areas tend to lessen the effect by excluding marginal contrast; and (since the eye tends to move along rather than across strongly marked lines), by hindering such motions of the eye as would bring about successive contrast. Repeat Ex. 152 *c*, using two slips of gray paper 5 mm. wide by 2 cm. long, and substituting a piece of moderately transparent letter-paper for the tissue paper. When the contrast color has been observed, trace the outline of one of the slips with a fine ink line upon the paper that covers it, and notice that the color nearly or quite vanishes. A disk like that in the cut accompanying Ex. 152 *d*, when provided with a second contrast ring, marked off on both its edges with a firm black line, shows a weakening of the induced color in the bordered ring.

This experiment and others like it play an important part in the psychological, as opposed to the physiological, explanation of simultaneous contrast; see Helmholtz, *A*, 543 ff., 559 f., Fr. 533 f., 539, 542, (406 f., 411, 414). Such a black border will, however, also make a weak objective color invisible.

d. Saturation. Contrast effects are generally most strik-

ing with little saturated colors. Compare the effect of increasing, decreasing, and extinguishing the second non-colored light in the colored shadow experiments. It is necessary, however, to see to it that reflected light from the walls and surrounding objects does not complicate the experiment.

Compare the intensity of the contrasts in Meyer's experiment (Ex. 152 *c*) before and after the application of the tissue paper. Notice also the part played by the white light mixed with the colored light in the mirror contrast experiments above. Try the effect of introducing white or black or both into the largest and smallest disks in the arrangement mentioned at the end of Ex. 152. Powerful contrasts with the most saturated colors can be observed, however, when the proper conditions are fulfilled.

e. Colors induced upon gray fields are stronger when the gray has about the same brightness as the inducing color. Repeat Meyer's experiment, using white paper instead of the gray or black. With the three disk arrangement try the effect of making the intermediate disk all white and all black. Rood finds that grays slightly darker than the inducing color are advantageous when the inducing color is red, orange, or yellow, and slightly lighter when the inducing color is green, blue, violet, or purple.

On conditions in general, see Helmholtz, *A*, 540–541, Fr. 513–514, (390–391), Kirschmann, *D*. In Hering, *E*, will also be found much on the effect of various conditions. On *b*, Exner, *B*. On *c*, Helmholtz, *A*, 546–547, Fr. 539–542 (411–414). On *d*, Helmholtz, *A*, Fr. 523–524 (399–400). On *e*, Rood, *A*, 261.

154. The Halo or *Lichthof* of Hering. Contrast is often to be seen in negative after-images. That observed in after-images of white objects on a dark ground has been adduced by Hering as an argument against the psychological explanation of contrast. Some of the simpler experiments are

as follows; for his development of them consult Hering, *A.*

a. Lay a half inch square of white paper on a large sheet of black cardboard (or better of black velvet), and put a small dot at its centre. Stare with unmoved eyes at the dot for from 15 to 30 seconds or more, then close and cover the eyes. There will then be seen, neglecting incidental color effects, the dark after-image of the paper surrounded by a halo of light, brightest next the paper and gradually falling off in brilliancy toward the periphery. This is explained on the psychological theory as due to contrast with the deep black of the after-image of the square. When, however, the converse of the experiment is properly made (a black square on a white ground), the dark halo which would be expected by contrast is not found, though the after-image of the black square is very bright.

b. Lay two white squares side by side two or three millimeters apart on the dark ground and between them a minute clipping of paper for a fixation point. Secure the after-images as before. The halos of the two squares coincide in the narrow space between and give a much brighter band in the after-image. Under favorable circumstances this bright band may remain visible while the after-images of the squares themselves are temporarily invisible. In both these experiments it is better to use both eyes than a single one. The explanation of the halo as a matter of false judgment, especially in the last mentioned case, is not easy. Hering, *A.*

155. Simultaneous Contrast with Colored Shadows. The effects of simultaneous contrast are almost always lost in the more powerful ones of successive contrast. The first requisite, therefore, of an experiment on the first, is the exclusion of the second. This is not difficult for colored shadows.

a. Place a good-sized piece of white paper on a table in such a position that it may be illuminated at the same

time from a window (if the day is overcast) and from a gas-jet. Set upon it a small block or other object (about 5 cm. by 10 cm. in size); something black in color is best. Light the gas and observe the two shadows, one cast by the light from the window, the other by the gas. The first will appear yellowish, the second clearly blue.[1] Adjust the distance and position of the block with reference to the light so that the shadows shall appear about equally dark, and the blue shadow shall be as sharply bounded as possible, and for that purpose it is well to have the shadow cast by the edge rather than the flat side of the flame. The color of the yellowish shadow is objective and due to the yellow of the gas-flame, that of the blue is due to the contrast, but largely, as yet, to successive contrast. Put a dot in the centre of the blue shadow, to serve as a fixation-point, and another on the edge. Fasten a paper tube (preferably blackened inside) so that it can easily be shifted from one dot to the other. Cut off the gas-light by holding a card between it and the block; adjust the tube so that the dot in the middle of the shadow may be fixated without any of the field outside of the shadow being seen. Wait until all of the blue has disappeared from the shadow, and then, still looking through the tube, remove the card. The field remains entirely unchanged and appears, as before, a colorless gray. The former blue color is thus shown to be subjective and due to contrast with the yellow lighted area in which it lies.

[1] This setting of the experiment succeeds best when the daylight is weak, as, for example, just before the lights are usually lighted in the evening. If the experiment is to be made in broad day, the light must be reduced by curtains or otherwise; if at night, there must be two lights, one corresponding to the window and one to the gas, and the latter must shine through a pane of colored glass. If yellow glass is used, the colors will be the same as those in this experiment, the free flame taking the place of the daylight. If the sky is clear, its light is itself blue, and would complicate the experiment somewhat. Its light may, however, be passed through colored glass or gelatine, but then the orange color of the gas-light must be regarded.

b. Cut off the gas-light again and adjust the tube so that the dot in the edge of the shadow may be fixated. Taking great care not to move the eye, withdraw the card. The part of the field of the tube filled by the shadow will appear bluish, that of the remainder reddish yellow. After a little time of steady fixation, cut off the gas-light once more and observe the instant reversal of the colors. The shadow now appears in reddish yellow, the rest of the field blue. The color of the shadow, both before and after the final interposition of the card, is due to simultaneous contrast, in the first case with the reddish yellow light, and in the second with its after-image.

Helmholtz and his supporters explain all cases of simultaneous contrast as errors of judgment; in the case of the colored shadow, for example, we mistake the yellow of the gas-lighted field for white, and consequently find the shadow which is really gray to be bluish. In the case of this particular experiment, Hering and Delabarre have shown this psychological explanation unnecessary and a physiological one all sufficient, and Hering has done the same for other forms of experiments.

On simultaneous contrast in general, see Helmholtz, *A*, 542 ff., Fr. 515–547 (392–418); Hering, *A* and *E*. On colored shadows see Helmholtz, *A*, 551–553, Fr. 517–519 (394–396); Hering, *E*; Delabarre.

On Helmholtz's theory see Helmholtz, *A*, 543 ff., Fr. 516, 533–538 (392, 407–411); Hering, *E*; Rood, *A*, 252 ff.; von Bezold, *B*, 146 ff.

For quantitative measurements of simultaneous contrast under various conditions, see Kirschmann, *D*.

156. Simultaneous Contrast. Hering's Binocular Method.

a. Set a red glass in the right frame of the binocular color-mixer, a blue glass in the left. Look fixedly through the colored glasses at the cork ball below, bringing the eyes close to the glasses and the nose between them. Adjust the side screens till the white ground below appears in a uni-

form light violet from the binocular mixture of the red and blue (see Ex. 167). The narrow strip of black paper on the white is seen double, the right hand image bluish, the left yellowish.

b. The possibility of successive contrast, however, is not yet excluded. Lay a sheet of black paper over the whole of the white field and its black strip; rest the eyes; and finally, when everything is in readiness, and the eyes again fixed on the ball, swiftly draw away the black paper, keeping the eyes motionless. The contrast colors are seen on the instant, before any motions of the eyes that might introduce successive contrast have been made.

Hering argues that this experiment is conclusive against the psychological explanation of simultaneous contrast, unless a separate unconscious judgment is to be made for each eye; for that which is seen is a light violet field, and the contrast color to that should be a greenish yellow, and both images of the strip should be alike, whereas, actually, the images appear in different colors, neither of which is the color required.

Hering, *J.*

157. Induction of a Like Color. An effect the reverse of the ordinary contrast effects sometimes appears, the inducing color reappearing in the induced field.

a. Place close side by side a large piece of black paper and an equal sized piece of white. Make a dot as a fixation point at the middle of their line of junction, and stare fixedly at it for half a minute. After a few seconds the white will appear decidedly darker and the black decidedly lighter, the effect becoming more marked as fixation is continued. See also Ex. 122.

b. A darkening or brightening of a colored ground is often to be observed when a figure in black or white is placed

upon it. This is a method of obtaining shades and tints often used in polychromatic decoration. Observe the effect in Fig. 4 of Plate I. The same may be observed occasionally in plaid fabrics, and is shown very satisfactorily in kindergarten mats woven in checker-board pattern of colored and gray papers. If a set of graded grays is used so that the strips may range evenly from a black at one side to a white at the other, the corresponding shading of the colored paper is striking.

On *a*, Helmholtz, *A*, 554 ff., Fr. 527 ff. (401 ff.); Hering, *A*, 36 ff. On *b*, von Bezold, *B*, 182–183 and Plate V. For what is perhaps a related phenomenon, see Brücke, 424 ff.; Helmholtz, *A*, 549, Fr. 520 (396); Aubert, *A*, 549 f.

158. Influence of Experience in Visual Perception. While in the previous experiments a physiological explanation seems sufficient for the facts, psychical action is not excluded, even by Hering, from a considerable share in sense perception. In the following experiments experience coöperates in the result.

a. Place upon the color-mixer a short-pointed star of white cardboard, or even a square; when in sufficiently rapid rotation, it appears as a white central circle surrounded by a more or less transparent ring. While in this condition bring behind it a broad strip of black cardboard of somewhat greater length than the diameter of the star from point to point. As the edge of the card advances, it can be seen not only behind the transparent ring, but, apparently, also behind the opaque central circle, and the portions of the latter in front of the black card seem darkened by its presence. The illusion holds, though with a lightening instead of a darkening effect, when a white card is moved behind a black star. The illusion fails by degrees if the card is kept motionless, but may be observed to a certain extent when the star is at rest, or even on a square of card-

board held in the hand while another is moved to and fro behind it. In all cases the latter card should often be wholly withdrawn, so that its edge can be clearly seen.

b. Cover a piece of black cardboard smoothly with tissue paper, and notice that it seems at first blacker (because its color is well known) than it afterwards proves to be on comparison with other grays.

c. In mixing colors by reflection (Ex. 150 *a*), notice the tendency to see one color through the other, instead of seeing the mixture of the two. This tendency may be so strong at first as to interfere, to a certain extent, with the success of the experiment. See also Ex. 164.

Helmholtz, *A*, 312, 323 f., Fr. 360 (273); Kirschmann, *E*. On the difficulty of judging small differences in the color of surfaces that present other small unlikenesses, see Hering, *E*.

Some Phenomena of Rotating Disks.

159. The Münsterberg-Jastrow Phenomenon. *a.* Set a black and white disk, e.g., that used in Ex. 145 *a*, in rapid enough rotation to give a uniform gray; pass rapidly before it a thin wooden rod or thick wire, and notice the multitude of shadowy images of the rod that appear on the disk. The number of images is greatest in the portion of the disk having the most frequent interchange of black and white.

b. Replace the disk by one carrying two or more colors. Notice the repetition of the phenomenon, and that the colors of the images are the colors (otherwise completely blended) which the disk actually carries. The explanation of the phenomenon is not altogether clear, but the sudden changes of the background against which the rod is seen seem to have an effect not unlike that of a stroboscopic disk or of intermittent illumination, and thus show the rod at rest in its successive positions.

Jastrow.

160. Retinal Oscillation. Prepare a disk of black cardboard 25–30 cm. in diameter, and paste upon it a sector of white of 90° extent. Put the disk in slow rotation (one turn a second), fixate the middle of the disk, and notice that the retreating edge of the black is always followed by a narrow shadowy sector in the white. Under favorable conditions more than one may be seen. The retina on first being stimulated with white, apparently reacts in the direction of black (see Ex. 125), then swings again toward white, and so on.

Charpentier, *B.*

161. Perception of Flicker with Different Parts of the Retina. Place upon the color-mixer a black and white disk in which the sectors are complete from centre to circumference; those used in Ex. 145 will not answer here. Rotate the disk at such a rate as to give a lively flicker, fixate its centre and slowly increase the rate. With care a point will be found where the sectors are blended for the central parts of the retina, but still flicker for the periphery. Try also looking at one edge of the disk while giving attention to the centre or opposite edge. This is in accord with the general principle that peripheral after-images are of shorter duration than those of the retinal centre. Too bright illumination should be avoided, for with intense light the difference between the centre and periphery is less, or even quite reversed.

Bellarminow. On rotating disks and their phenomena in general, see Helmholtz, *A*, 480–501, Fr. 445–471 (337–357).

Binocular Phenomena of Light and Color.[1]

162. In general the two eyes co-operate to bring about a single visual result, but the union of the impressions upon the two retinæ is influenced by a number of circumstances.

[1] The experiments that follow can all be made with the stereoscope, but practice will enable the experimenter to combine the diagrams with free eyes, either by crossing the lines of sight (fixating a point nearer than the diagram), or by making them parallel or nearly so (fixating a point beyond the diagram). This

a. If the stimulus to one eye is considerably stronger than that to the other, the sensation in the latter is in most cases totally suppressed. Close one eye and look at a sheet of white paper with the other, letting the open eye move about freely. There is no tendency for the darkened field of the closed eye to assert itself.

b. When, however, the effect of the stimulus in the open eye is somewhat weakened by steady fixation, such a tendency is to be observed, and the whole of the field of the open eye, except a small area about the point fixated, may be suppressed from time to time by the dark field of the closed eye. A slight motion will, however, instantly restore the first. See also Ex. 127.

c. A field that contains sharply marked objects or contours will generally triumph over one that does not. Try combining the letters below in such a way that the B's are superposed. In this diagram the white field of either eye, which corresponds to A or C in the other eye, will generally not triumph over the letter.

AB BC

Helmholtz, *A*, Fr. 964 ff. (767 ff.); Hering, *P*, 380–385; Aubert, *A*, 550–553; Wundt, *A*, 3te Aufl., II., 183 ff., 4te Aufl., II., 209 ff.

163. Fechner's Paradoxical Experiment. Hold close before one eye a dark glass, such as is used in protecting the eyes, or a piece of ordinary glass moderately smoked over, or even a black card with a good-sized pin-hole in it, allowing the other eye to remain free. It is easy to see that the

skill the experimenter should try to acquire. In these experiments it is important that the eyes should be of approximately equal power; and if the poorer eye cannot be helped with lenses, the vision of the other must be somewhat reduced by the interposition of a sufficient number of plates of ordinary glass.

binocular field is darkened by the interposition of the dark glass. If, however, the eye behind the glass is closed, or the light wholly cut off from it by holding a black card in front of the glass, the field appears decidedly brighter; that is to say, cutting off a portion of the stimulus received by the total visual apparatus, has caused an increased intensity of sensation. The experiment fails for very dark and very light glasses. Several explanations have been given, but that of Aubert (according to which the sensations of the two retinæ blend in a sort of average result when the difference is not too great, but one wholly suppresses the other when the difference is very great) seems to be the most satisfactory.

Fechner, *B*, 416 ff.; Helmholtz, *A*, Fr. 993-994 (790-791); Hering, *Q*, 311 f.; Aubert, *A*, 499-503.

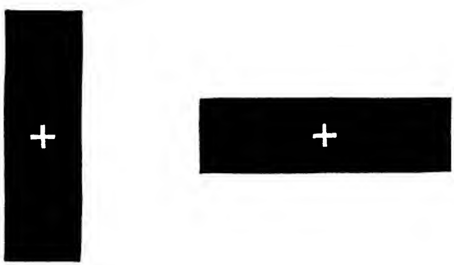
164. Rivalry. When the two retinæ are stimulated at the same time separately with strong light of different colors, or are confronted with otherwise incongruous fields, i.e., fields that cannot be given a unitary interpretation, there results a peculiar instability and irregular alternation of the colors over part or the whole of the combined fields of vision. This apparent struggle of the fields is known as Retinal Rivalry. Hold close before one eye a piece of blue glass, before the other a piece of red glass, and look toward the sky or a brightly lighted uniform wall. The struggle of colors will at once begin. The same may be observed with a stereoscope when the usual paired photographs are replaced by colored fields, or even with no apparatus at all, when both eyes are closed and turned toward a bright sky and one of them is covered with the hand. Long looking generally tends to quiet the rivalry. Rivalry has been explained as due to fluctuations of attention, and some observers find that it can be more or less controlled by attention (Helmholtz). Fechner discusses the attention

theory, and finds it insufficient. Von Bezold thinks rivalry associated with changes in accommodation which follow attention. Hering and others regard the changes as of more purely physiological origin. See also Ex. 165 *b*.

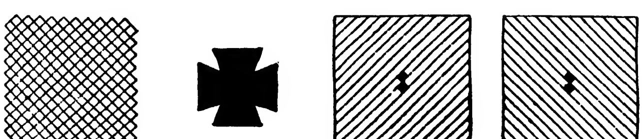
Helmholtz, *A*, Fr. 964 ff. (767 ff.), 974 ff. (775 ff.); Hering, *P*, 380–385, *Q*, 308 ff.; Aubert, *A*, 550 ff.; Wundt, *A*, 3te Aufl., II., 185 ff., 4te Aufl., II., 211 ff.; Chauveau, *C*.

165. Prevalence and Rivalry of Contours. By contours is here meant lines of separation where fields of one color border upon fields of another color.

a. Combine stereoscopically the two bars below, and notice that it is the contours that suppress the solid parts of both the black and white. This figure gives excellent results also when colors are substituted for the black and white.



Notice a similar triumph of the contours of the cross in the left-hand figure below, or, better still, in an enlargement of it.



b. Notice the rivalry of the contours in all of these figures.

c. The last two pairs of diagrams are suitable for the study of the part played by attention in rivalry. While it is doubtful whether mere attention to one field or the other can cause it to predominate, it yet seems possible by indirect application of attention to cause it to do so. If attention is given to an *examination* of the lines and small squares in the left-hand figure, or if one of the sets of lines in the right-hand figure is counted, both will appear to be somewhat assisted in their struggle with the cross or the other set of lines.

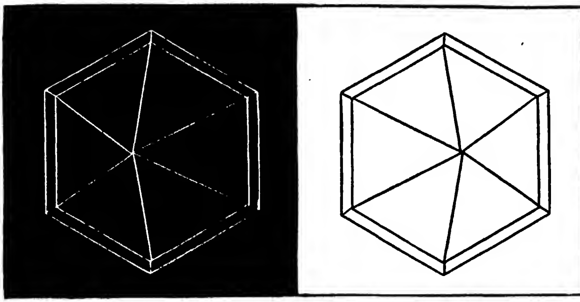
d. A printed page has a decided advantage. Try a diagram in which a printed page is put in rivalry with a field of heavy cross lines. The lines will be found to yield to the print, at least at the point at which the reader is looking at the instant. Two printed pages, however, become hopelessly mixed; and it is hard to say how much of the advantage, when a single one is used, is due to its superior power as a holder of attention, and how much to its excellence as a set of contours. A portion of the power of contours is probably to be explained by the mutual intensification of both the black and the white by contrast; but a part is perhaps due to a strong tendency, observable in other cases also, for the eyes (and attention) to follow lines, and especially outlines.

Helmholtz, *A*, Fr. 964 ff. (767 ff.); Hering, *P*, 380–385, *Q*, 314; Wundt, *A*, 3te Aufl., II., 183 ff., 4te Aufl., II., 209 ff.

166. Luster. Sheen. When one of the rival fields is white and the other colored (especially when one is white and the other is black), there results, besides the rivalry, a curious illusion of shine or polish, known as binocular lustre.

a. Examine in the stereoscope a diagram made like the accompanying cut, and notice the graphite-like shine of the

pyramid. The explanation seems to be that polished surfaces, which at some angles reflect light enough to look



white, and at others appear in their true color, have often in previous experience given rise to such differences of sensation in the two eyes, and from this difference it is inferred that the object seen in the diagram is shiny.

b. A species of monocular lustre (or transparence) is to be observed when black or white or colors are combined by means of the reflection color-mixer, especially when the inclination of the plate is so changed that one color appears to be reflected in the surface of the other, or to be seen through and behind it. The experiment works well when real objects are reflected in the surface of the glass, the reflecting power of the latter appearing to be transferred to the horizontal surface on the opposite side.

Helmholtz, *A*, Fr. 983 ff. (782 ff.); Hering, *P*, 576–577; Aubert, *A*, 550 ff.; Wundt, *A*, 3te Aufl., II., 177 ff., 183 ff., 4te Aufl., II., 204 ff., 209 ff.

167. Binocular Color Mixing. The result of simultaneous presentation of different colors to the two eyes is not always rivalry or lustre. If the colors are not too bright and saturated, and the fields are without fleck or spot to

give one the predominance, a veritable, though somewhat unsteady, mixture of the colors may result.

a. Place a red and a blue glass of equal transparency in the binocular color-mixer, and adjust the side screens till the proper amount of white light is mixed in with that transmitted from below. The mixture will then be seen on the white field below. Try also with other combinations of glasses. Mixtures obtained in this way are not always the same in appearance as the monocular mixtures studied above, and some observers have great difficulty in getting them satisfactorily. Long and steady gazing, which interferes with rivalry, favors binocular color mixing.

b. The same effect may be conveniently obtained with a stereoscope, from which the middle partition has been removed. Try with equal areas of dull colors of little saturation. Hering recommends two squares of red and two of blue, set at equal distances in a horizontal line, the two reds on one side, the two blues on the other. When the middle pair are combined stereoscopically, they show a mixed color, while the unmixed colors can be seen for comparison beside them. He also suggests the use of lenses to prevent sharp focusing of the eyes upon the contours, which interferes with the mixture. Complementary colors are said to be more difficult to fuse than those standing nearer in the color scale. The same is true of colors differing greatly in brightness; see Ex. 163.

Helmholtz, *A*, Fr. 976 ff. (776 ff.); Hering, *P*, 591-600; von Bezold, *C*; Chauveau, *A*; Aubert, *A*, 550 ff.; Wundt, *A*, 3te Aufl., II., 183 ff., 4te Aufl., 209 ff.

168. Binocular Contrast. The Side-Window Experiment. Stand so that the light from the window falls sidewise into one eye, but not at all into the other. Place in a convenient position for observation a strip of white paper on a black surface. The paper when looked at with both eyes appears

perfectly colorless. On looking now at a point nearer than the strip of paper (e.g., at the finger held up before the face), double images of the strip will be seen. The two images will be different in brightness and slightly tinged with complementary colors. The image belonging to the eye next the window (which may be recognized by its disappearance when that eye is closed) will appear tinged with a faint blue or blue-green color, the other with a very faint red or yellow. The light that enters the eye through the sclerotic is tinged reddish yellow, and makes the eye less responsive to that color; the white of the paper strip therefore appears bluish. It appears darker partly for a similar reason, and perhaps also, as Fechner suggests, because it lies in a field which, for the eye in question, is generally bright. The reddish color of the other eye's image of the strip is explained as due to contrast with the first, but whether this contrast color is a psychical matter, or whether it is to be explained by the action of the stimulus in the first eye upon the second, as there seems some reason to think, is as yet uncertain. Its greater brightness is probably due to the fresher condition of the eye to which it belongs, and to contrast with its less brilliant field. The same thing is often to be noticed when reading with the lamp at one side, or even when one eye has been closed for a short time while the other has been open. The double images are in no wise essential; simple alternate winking will show decided differences in the condition of the two eyes.

Fechner, *B*, 511 ff.; Brücke, 420 ff.; Hering, *P*, 600–601; Helmholtz, *A*, Fr. 987 ff. (785 ff.); Chauveau, *B*; Titchener; Wundt, *A*, 3te Aufl., II., 183 ff., 4te Aufl., II., 209 ff.

169. Binocular After-Images. Lay a bit of orange-colored paper on a dark ground, and provide two white cards. Hold one of the cards close to the left eye, but a little to one side, so as not to hide the bit of paper. Hold the other

eight or ten inches from the right eye in such a way as to hide the paper. Look at the paper for a few seconds with the left eye, then bring the card before it. A faint, washy, orange-colored positive after-image will appear on the card before the right eye. The image is by no means easy to observe. It is supposed to belong to the right eye's half of the visual apparatus, possibly to the central, i.e., cerebral, part.

Ebbinghaus, *C*; Chauveau, *B*; Titchener.

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I. Die Untersuchung einseitiger Störungen des Farbensinnes mittels binocularer Farbengleichungen, *ibid.*, XXXVI., 1890, iii., 1–23.

J. Beitrag zur Lehre vom Simultankontrast, *Zeitschrift für Psychologie*, I., 1890, 18–28.

[1] Hering's work upon color has not yet been gathered into one consecutive whole. It has seemed well, therefore, to insert here, in addition to the titles of papers bearing directly on the experiments of Chap. VI., such other titles on light and color as came to hand.

K. Eine Methode zur Beobachtung des Simultancontrastes, *Pflüger's Archiv*, XLVII., 1890, 236–242.

L. Prüfung der sogenannten Farbendreiecke mit Hülfe des Farbensinns excentrischer Netzhautstellen, *ibid.*, XLVII., 1890, 417–438.

M. Ueber Newton's Gesetz der Farbenmischung, Prag, 1887. Reprint from *Lotos*, VII., 1887.

N. Untersuchung eines total Farbenblinden, *Pflüger's Archiv*, XLIX., 1891, 563–608.

O. Eine Vorrichtung zur Farbenmischung, zur Diagnose der Farbenblindheit und zur Untersuchung der Contrasterscheinungen, *Pflüger's Archiv*, XLII., 1888, 119–144.

P. Work cited with reference letter *A* in the bibliography of Chap. V.

Q. Work cited with reference letter *B* in the bibliography of Chap. V.

R. Ueber Holmgren's vermeintlichen Nachweis der Elementarempfindungen des Gesichtssinns, *Pflüger's Archiv*, XL., 1887, 1–20.

S. Kritik einer Abhandlung von Donders, *Lotos*, Neue Folge, II., Prag, 1882.

T. Ueber Sigmund Exner's neue Urtheilstäuschung auf dem Gebiete des Gesichtsinnes, *Pflüger's Archiv*, XXXIX., 1886, 159–170.

U. Ueber den Begriff „Urtheilstäuschung" in der physiologischen Optik und über die Wahrnehmung simultaner und successiver Helligkeitsunterschiede, *ibid.*, XLI., 1887, 91–106.

HESS: *A*. Ueber den Farbensinn bei indirectem Sehen, *v. Graefe's Archiv*, XXXV., 1889, iv., 1–62.

B. Untersuchung eines Falles von halbseitiger Farbensinnsstörung am linken Auge, *ibid.*, XXXVI., 1890, iii., 24–36.

C. Ueber die Tonänderungen der Spektralfarben durch Ermüdung der Netzhaut mit homogenem Lichte, *ibid.*, XXXVI., 1890, i., 1–32.

HILLEBRAND: Work cited in bibliography of Chap. V.

HOLMGREN: Color-blindness in its Relation to Accidents by Rail and Sea. Translation by M. L. Duncan, *Smithsonian Report*, 1877, 131–195.

JASTROW: A Novel Optical Illusion, *American Journal of Psychology*, IV., 1891–92, 201–208.

JEFFRIES: *A.* Color-blindness, its Dangers and its Detection, Boston, 1879. This work contains a seventeen-page bibliography on color-blindness and kindred topics.

B. Color-blindness, Article in the Reference Handbook of the Medical Sciences, New York, 1886, II., 241.

KIRSCHMANN: *A.* Beiträge zur Kenntniss der Farbenblindheit, *Wundt's Philos. Studien*, VIII., 1892–93, 173–230, 407–430.

B. Ueber die Helligkeitsempfindung im indirecten Sehen, *ibid.*, V., 1889, 447–497.

C. Die Farbenempfindung im indirecten Sehen, Erste Mittheilung, *ibid.*, VIII., 1892–93, 592–614.

D. Ueber die quantitativen Verhältnisse des simultanen Helligkeits- und Farben-Contrastes, *ibid.*, VI., 1890, 417–491.

E. Some Effects of Contrast, *American Journal of Psychology*, IV., 1892, 542–557.

KÖNIG: *A.* Ueber den Helligkeitswert der Spektralfarben bei verschiedener absoluter Intensität, Beiträge zur Psychologie und Physiologie der Sinnesorgane (Helmholtz Festgruss), Hamburg und Leipzig, 1891, 311–388.

B. The Modern Development of Thomas Young's Theory of Colour Vision, *Report of British Association, Birmingham Meeting*, 1886, 431–439.

C. Zur Kenntniss dichromatischer Farbensysteme, *Wiedemann's Annalen*, XXII., 1884, 567–578.

KÖNIG UND DIETERICI: *A.* Die Grundempfindungen in normalen und anomalen Farbensystemen und ihre Intensitätsverteilung im Spektrum, *Zeitschrift für Psychologie*, IV., 1892, 241–347.

B. Ueber die Empfindlichkeit des normalen Auges für Wellenlängenunterschiede des Lichtes, *Wiedemann's Annalen*, XXII., 1884, 579–589.

VON KRIES: Die Gesichtsempfindungen und ihre Analyse, *Du Bois-Reymond's Archiv*, 1882, Supplement-Band, 1–178. A careful summary and discussion of the whole subject.

LEHMANN: Ueber die Anwendung der Methode der mittleren Abstufungen auf den Lichtsinn; die quantitative Bestimmung des Lichtcontrastes, *Wundt's Philos. Studien*, III., 1886, 516–528.

MAXWELL: *A.* On the Theory of Compound Colours, and the Relation of the Colours of the Spectrum, *Phil. Trans.*, CL., 1860, 57–84.

B. On Colour Vision, *Proc. Royal Institution of Great Britain*, VI. These two papers are also to be found in Maxwell's Scientific Papers, Cambridge, 1890, I., 410–440, II., 267–280.

MAYER: Studies of the phenomena of Simultaneous Contrast-Color; and on a Photometer for measuring the intensities of Lights of different colors, *American Journal of Science*, Ser. 3, XLVI., 1893, 1–22; also *Phil. Mag.*, Ser. 5, XXXVI., 1893, 153–175.

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NICHOLS: *A.* On the Sensitiveness of the Eye to Colors of a Low Degree of Saturation, *American Journal of Science*, Ser. 3, XXX., 1885, 37–41.

B. Duration of Color Impressions upon the Retina, *American Journal of Science*, Ser. 3, XXVIII., 1884, 243–252.

PACE: Zur Frage der Schwankungen der Aufmerksamkeit nach Versuchen mit der Masson'schen Scheibe, *Wundt's Philos. Studien*, VIII., 1892–93, 388–402.

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PLATEAU: Betrachtungen über ein von Hrn. Talbot vorgeschlagenes photometrisches Princip, *Poggendorff's Annalen*, XXXV., 1835, 457–468.

POLE: Further Data on Colour-Blindness, *Phil. Mag.*, Ser. 5, XXXIV., 1892, 100–114, 439–443, XXXV., 1893, 52–62, XXXVI., 1893, 188–195.

PREYER: Work cited in bibliography of Chap. I.

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B. Rayleigh and others: Report of the [Royal Society's] Committee on Colour-Vision, *Proc. Roy. Soc.*, LI., No. 311, July 19, 1892, 281–396.

ROOD: *A.* Students' Textbook of Color, New York, 1881.

B. On a new Theory of Light, proposed by John Smith, M.A., *American Journal of Science*, Ser. 2, XXX., 1860, 182–186.

SCHUSTER: Experiments with Lord Rayleigh's Colour Box, *Proc. Roy. Soc.*, XLVIII., 1890, 140–149.

TALBOT: Experiments on Light, *Phil. Mag.*, Ser. 3, V., July–Dec., 1834, 321–334, especially, 327–334.

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WUNDT: *A.* Work cited with same letter in the bibliography of Chap. V.

B. Die Empfindung des Lichts und der Farben, *Wundt's Philos. Studien*, IV., 1888, 311–389.

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CHAPTER VII.

Visual Perception of Space and Motion.

THE question of visual space perception is one of the oldest and most actively discussed in all physiological psychology. A complete treatment involves arguments from surgery, pathology, and other sources outside the possibilities of the laboratory; and even then it is difficult, if not impossible, to establish one theory of it surely, as against all others. Apart from the question of original sensations, there is, however, a certain degree of harmony, and it is the commonly accepted facts that this chapter aims to gather up. The discussion of the ultimate matters may be followed in the works of Helmholtz, Hering, Stumpf, James, Wundt, and others. For the facts in general, see Helmholtz, Hering, Aubert, Wundt, James, and Le Conte; for special facts, see special references given below. The subject is also treated in the standard physiologies, Bernstein's Five Senses, McKendrick and Snodgrass's Physiology of the Senses, and other books of the same kind.

The ordinary seeing of space rests on the retinal and kinæsthetic sensations of both eyes, and in every normal act of vision any or all these sensations may be influential. For the sake of simplicity, however, it is necessary to separate them, and to treat now one and now another. The topics will be taken up in the following order: Monocular Perception of Space (including cases where both eyes are used, but the conditions are not essentially influenced thereby); Geometrical Illusions; Equivocal Figures; Binoc-

ular Perception of Space; Visual Perception of Motion; and Visual Symmetry.

MONOCULAR PERCEPTION OF SPACE.

170. The Outward Reference of Visual Perceptions. Outward reference of visual perceptions probably comes about through their co-ordination with the perceptions of other senses, especially the tactual and kinæsthetic, but the matter is too complex for direct experiment. It is easy, however, to study the relation of the retinal image to the outer objects that produce it. Considered physically, the image is reversed. (Cf. the experiment on the rabbit's eye, Ex. 104, and those on Purkinje's vessel figures and phosphenes, Exs. 111 and 119): it can be shown also in the following experiment with retinal shadows; but in all cases it must be kept clearly in mind that retinal phenomena are never perceived as such, and especially that retinal sensations are not first given a location in the eye, and later transferred outward.

a. Retinal Shadows; Le Cat's Experiment. Hold a pin, head upward, as close as possible before the pupil, and, an inch or two in front of the pin, a card pierced with a pin-hole. Move the pin about till it comes into exact line with the hole, when there will be seen in the circle of diffusion representing the hole a shadowy inverted image of the pin-head, somewhat as appears in the accompanying cut.

The rays of light from the pin-hole are too divergent to be brought to a focus on the retina, but enter the eye in a favorable state for casting a shadow. The shadow on the retina is erect, like the pin that casts it, but is perceived as inverted. Observe at the same time the still more blurred, erect image of the pin through which the

other things are seen. This is not a shadow, but an image (really a blur of diffusion circles) formed in the ordinary way by light reflected from the surface of the pin. When several pin-holes are used (three at the points of an eighth of an inch triangle, for example), an equal number of shadows will be seen.

The casting of the shadow can easily be illustrated with a candle and a double convex lens. Set the lens a foot or two from the candle, and hold a card on the opposite side of the lens, too near for the formation of an image; then introduce a finger or pencil close before the lens on the side toward the light, and observe the erect shadow on the card.

b. After-Images and other retinal phenomena often appear to be conformed to the surface of objects upon which they are projected. This has been made a subject of experiment in Ex. 124 *b*, and another example was found in the distortion of the after-image cross in Ex. 131 *b*. If the surface is complicated and the after-image strong, this conformation is not apt to occur, the image appearing instead to float before the surface. Get a monocular after-image of a narrow slit in the window shutters, or of a polished steel rod set up in the sunlight, and project it into one corner of the room. The after-image, especially when somewhat faded, can be made to lie part on one wall and part on another, and thus to appear bent and distorted.

On monocular projection in general, see Helmholtz, *A*, G. 758 ff., Fr. 780 ff. (613 ff.); Aubert, *A*, 600 ff., 619 f.; Hering, *A*, 572 ff. On *a*, Le Conte, *B*; Wallenberg; Laqueur. On *b*, Thiéry, 315 f.; Scharwin and Novizki.

171. Monocular Perception of the Directions from the Eye. The perception of direction is ordinarily binocular, and the centre to which directions are referred lies between the eyes, even when one is closed. (See Ex. 207.) Binocular

perception must, however, rest on a perception of the relative direction of points in the monocular field, and this will be considered in the next few experiments.

Two luminous points appear to have the same direction when one is exactly covered by the other; or, to state the matter in retinal terms, when the image of the one for which the eye is accommodated lies in the centre of the circle of diffusion of the one for which the eye is not accommodated; or, if both appear in diffusion circles, when the centres of these circles coincide. The lines drawn through points in this relation are known as *Sighting Lines.* When prolonged toward the eye, they meet in the centre of the pupil, or, rather, in the centre of the image of the pupil formed by the cornea, about 0.6 mm. forward of the true position of the pupil, and 3 mm. from the summit of the cornea.[1] The sighting line which coincides with the line of vision is the *primary sighting line.*

The Parallax of Indirect Vision. The position of the common point of sighting-lines is found by inference from the optical structure of the eye. To make a sure empirical determination would be laborious, but it is easy to show

[1] These lines (*Visirlinien, Lignes de visée*) might well be called "lines of direction," had not this name been already given to another set of lines, those, namely, which are drawn from the points of external objects to the corresponding points of the retinal image. These have been mentioned in Exs. 106 and 117; and they give, with certain limitations, the directions in which objects appear when the eye is exactly accommodated for them. Their point of intersection is about 7 mm. from the summit of the cornea. They are important for physiological optics, but for the psychology of the perception of direction are less important than the sighting lines, though for remote points, and for points near the fixation point, the difference between the two sets of lines is very slight. For points remote from the fixation point, for reasons to be given later (Ex. 172), neither set gives exactly the direction in which objects are seen.

Kirschmann (p. 474 ff.) has called attention to an error into which the unwary are apt to be led by the term "crossing point of sighting lines;" namely, that these lines, when extended to the retina, give the position of the centres of the circles of diffusion. A more appropriate name for the point in question would be the *common point of sighting lines.* For diagrams correctly drawn in this particular see Kirschmann, Figs. 4–6.

that the point is considerably in front of the centre of rotation of the eye (about 10.6 mm.). The difference between the visual angle of any point (that is, the angle made by the sighting line passed through that point and the primary sighting line) and its rotational angle (that is, the angle through which the eye must be turned to fixate that point) is the *parallax of indirect vision.*

Place a candle at a distance of a foot or a foot and a half from the eye. Look toward the flame with a single eye, but hold close before the eye a pencil or narrow strip of cardboard. So long as the eye looks straight forward, the flame is entirely hidden by the pencil. When, however, the eye is turned strongly to either side, the flame instantly appears on the side toward which the eye has been turned. Such differences in apparent direction will be large if one of the points is near and the movements of the eye are extensive, but small when both points are distant or the movements small. Similar shiftings are caused by changes of accommodation. Dr. Kirschmann considers such changes an important element in the monocular perception of distance.

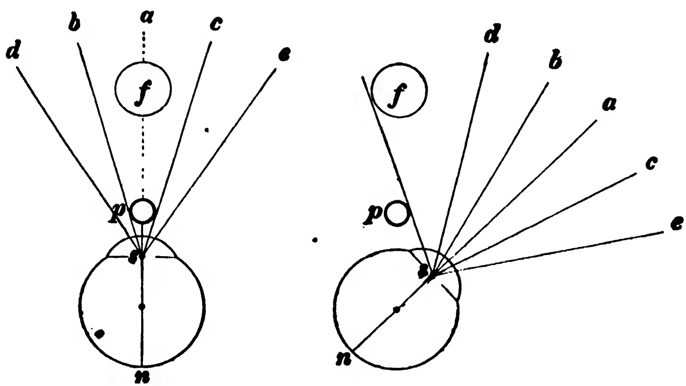
The explanation of the parallax will readily appear from the following diagrams, in which *p* represents the pencil, *f* the flame, *s* the common point of sighting lines, and the dot on *sn* the centre of rotation. The lines radiating from *s* are sighting lines, *sa* being the principal one, which is practically coincident with the line of sight.

Helmholtz, *A*, G. 680, 727 ff. Fr., 692 (539), 745 ff. (583 ff.); Aubert, *A*, 461; Kirschmann.

172. Relative Directions in the Monocular Field of Vis-

[1] For direction of the apparent vertical, which might also be included here, see Ex. 209 *b*.

a. Lines that Appear Straight in Indirect Vision. Lay a large sheet of paper on the table, and mark a fixation point in the middle of it. Two or three inches to the right or left of the fixation point place a button or bit of black paper, and, a foot farther and nearer, other buttons or bits of paper. Then leaning over the table so as to bring the eye above the fixation point, try to place the three buttons in a straight line, parallel to the median plane, holding the eye steadily upon the fixation point. Examination of the buttons when placed will show that the middle one is too



near the fixation mark; i.e., the attempt to make a straight line has resulted in a curve convex toward the fixation point. Try also with the buttons in lines perpendicular or inclined to the median plane.

If lines convex toward the fixation point appear straight, lines that are actually straight should appear concave. On a large sheet of paper draw a pair of parallel lines three or four inches apart and two or three feet long. Place a fixation point midway of their length and half-way between them; fasten the paper to the wall, or spread it on the

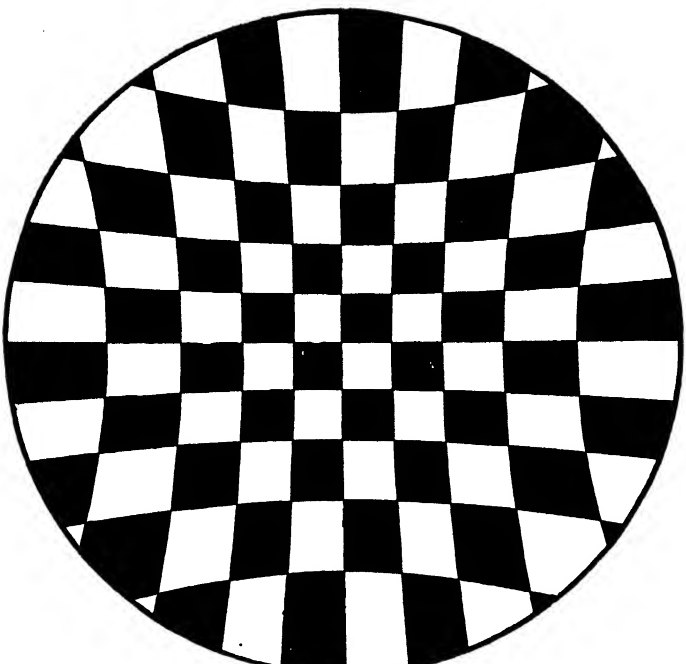
table, and observe as above. Try with the lines vertical, horizontal, and in oblique positions. In a spherical field of vision, the parallel lines of this experiment would be represented by great circles. The horizontal pair, for example, would have their poles at the right and left ends of the horizontal axis of the spherical field, and their planes would make equal angles above and below the plane of the horizon.[1]

It is obvious that changes in direction which make straight lines appear curved cannot take place without introducing slight errors of distance also. The shortest distances for perception are the curves which appear straight.

b. Nature of Lines that Appear Straight in Indirect Vision. It would, of course, be possible by developing the method used in *a* to make a somewhat exact study of the nature of these lines, but their general nature may be found in another way. In the hemispherical field of regard these lines are circles, — Helmholtz's *Circles of Direction*. The following diagram shows the projection on the plane field of a system of these circles of direction. For use, the diagram must be enlarged five or six times. It should be viewed with the single eye opposite its centre, and at a distance proportional to the length of the short line below the diagram. In order to fix this distance, it is convenient to cut a rod of such length, that when the eye is at the right distance the rod will just reach from the outer edge of the socket of the eye to the diagram. When the head is brought into the proper position, and the eye is fixed on the middle of the diagram, the lines of the figure will appear approximately straight and parallel. Try with the diagram in the position shown below, and also when turned so as to make

[1] It should not be supposed that the naïve field of vision is hemispherical. The field is neither definitely hemispherical nor definitely anything else, except as it is formed by the conditions and habits of vision. It is here spoken of as a hemisphere or as a plane, as case in exposition may require.

the principal lines oblique. Especial care should be taken to avoid movements of the eyes, for a new interpretation of the curves is thus introduced, and the checker-board seems concave instead of plane. This disadvantage may be escaped by fixating the centre of the diagram till a sharp and strong after-image is secured, and then observing this with closed eyes.



After getting the general effect, the observer should repeat the observation, beginning first at a distance greater than that just used, at which the curvature of the lines can

easily be recognized, and then slowly approaching till a point is reached where the lines seem straight and the squares equal, and still farther till the curves appear to bend the other way. Test the distance at which the lines seem straight with the little rod mentioned above; it will generally be found to agree approximately with the distance for which the diagram is calculated.[1]

It thus appears that the projections of the circles of direction are the lines that seem straight in indirect vision. These circles of direction are lines along which the eye (when moving according to Listing's Law) can carry a short after-image without causing the image to leave the line. They are in this particular, for the eye in motion, like straight lines, and the experiment shows that, even when the eye is kept still, its experiences of movement exercise a controlling influence on its perceptions. (On Listing's Law and the circles of direction, see Ex. 131 *b*, and Appendix I.)

c. Illusions of Form in Indirect Vision. Radial distances, as might be inferred from the diagram of *b*, are more decidedly underestimated than distances parallel to the margin of the field. Disks of cardboard or circles when removed a little from the fixation point appear flattened. Try with a six-inch disk held at arm's length, or an inch circle on cardboard (or the larger circle in the last figure in Ex. 197 *a*). Too great distance from the fixation point is a disadvantage; try on the four principal meridians of the retina at distances not greater than the diameter of the disk or circle.

[1] The agreement is not perfect, and there are perhaps, in addition, individual differences depending on the exactness with which the eyes follow Listing's Law. Helmholtz finds the curvature of the extreme verticals on the temporal side a little too great; and Küster, working by a slightly different method, appears to have found it too great for all the curves (cited by Hering, *A*, 370, note).

The whole field of vision itself appears narrower than it really is; it actually covers an extent of about 180°, and yet under favorable circumstances, as when looking at the dark field of the closed eyes, or at the sky in the absence of all landmarks, the extent may seem not much over 90°.

Helmholtz, *A*, G. 692 ff., Fr. 706 ff. (551 ff.); Wundt, *A*, 4te Aufl., II., 128 ff.; Hering, *A*, 369 ff., 536 ff.

173. Directions in the Monocular Field of Regard.[1] The observation that the perceptions of the eye at rest are modified by those of the eye in motion, is still further confirmed by the similarity of other phenomena of the field of regard and the field of vision.

a. Straight Lines Viewed with the Eyes in Secondary Positions. Experiment with a single eye and a long ruler held horizontally before an even wall space or other uniform background. Hold the flat side of the ruler toward the face, and about a foot distant from it. Try first with the ruler eight or ten inches above the primary position of the line of sight (cf. p. 119), running the eye freely back and forth along the edge, and observe that the edge appears curved upward; i.e., concave below. Try with the ruler depressed a somewhat greater distance below the primary position, and observe the contrary curvature. Try also with the ruler vertical and to the right and left. Little advantage will result from too extreme positions of the ruler. The curvature to be observed is not very great; but that it is due to the visual apparatus, and not to the ruler, is easy to show by turning the ruler over, which would reverse the direction of an actual curvature in the ruler, but not that of the curvature which depends on the

[1] The *Field of Regard* is the extent of space that can be seen directly when the eye is free to move; in other words, the field within which the fixation point may range.

eye. Change of position of the ruler from above to below the primary position of the eye, on the contrary, reverses the direction of the curvature due to the eye, but not a real curvature of the ruler. Compare the results here found with those in Ex. 172 *a*.

The occasion of the illusion is the rotation of the eyes when moved from point to point in secondary positions. (Cf. Ex. 131 *b*, and Appendix I.) When the eye is kept fixed on the end of the ruler, or moved slowly, the ruler may seem slightly tilted instead of curved.

Helmholtz, *A*, G. 686, Fr. 699 (545); Hering, *A*, 536.

174. The Retinal Image and Perception of Size. Accuracy of Discrimination. The perception of size is usually complicated by that of distance as well; but when objects are at the same distance, their relative size will depend on the size of their retinal images, if the eye is at rest, or on that and the extent of the angles through which the eye must be moved to sweep over them, if it is in motion.[1]

a. Accuracy of Comparison with the Eyes at Rest. Test with Galton's bar and the krypteon as follows. Place upon the middle of the flap of the instrument a small point to serve as a fixation point, and a guide-mark on the back-board to help in placing the bar so that its division thread may be each time exactly behind the mark on the flap.

[1] The size of the retinal image is found, as explained in Ex. 117, by ing lines from the extreme points of the object through the crossing point of the lines of direction, and prolonging them to the retina. The angle made by these lines is often called the *Visual Angle*. This construction, however, is exact only when the eye is exactly accommodated. When the eyes are not accommodated, the sighting lines should be used to form the angle instead of the lines of direction. And when objects are seen by sweeping the eye over them from end to end, the lines which give the true visual angle are obviously those from the extremities of the object to the centre of rotation of the eye. These various kinds of visual angles differ but slightly among themselves, and, as a matter of fact, are all purely artificial. Immediate perception knows nothing of visual angles or retinal images, but only things seen.

Adjust the Galton bar so that its division thread is in the middle. Place it in the krypteon, and cover it with the flap. Let the subject fixate the point on the flap; and when he is quite ready, let him quickly turn down the flap, and, keeping his eyes unmoved, make his judgment as to the equality of the two parts of the bar. If the parts seem unequal, a constant error in his judgment is probable, and the setting must be made such as to compensate it. If the parts seem equal, record the judgment, remove the bar, and alter the setting slightly. Replace the bar as before, with the division thread behind the fixation mark, and require a new judgment. Repeat this process, gradually increasing the displacement until the subject is just able to recognize a difference in the parts of the bar. Record the difference of length required for this judgment, and continue the experiment, beginning this time, however, with the parts quite distinctly unequal and working gradually toward equality.

A number of determinations should be made when the thread is displaced toward the right and toward the left, and with changes toward equality and away from it — an equal number of each kind — and the average of all taken. The ratio of the just observable difference to the length of one part of the bar is the measure of the accuracy of discrimination required. Averaging the results separately for the cases in which the thread is displaced towards the right and towards the left, will show the constant error in judgment, if there is any. It might seem profitable to furnish the subject with a head-rest, in order to secure a constant distance between his eyes and the bar; but there is reason to think this relatively unimportant (v. Kries, p. 187), and at all events, it is not necessary for casual testing. Care should be taken, however, that the distance is not such as to bring one end of the bar into the part of

the field corresponding to the blind spot. Movements of the eyes from end to end of the bar must be excluded, and, with care on the part of the subject, there should be no great difficulty in doing so. Of course, any trials in which movements occur should be reported and dropped from the record. If more perfect exclusion of eye-movements is desired, it may be obtained by placing the bar in a dark box, and using instantaneous illumination.

b. Accuracy of Comparison with Movement of the Eyes. Repeat the experiment with all conditions as in *a*, except that after the showing of the bar the subject be allowed to move his eyes freely in comparing the parts. Compare the results found in *a* and *b*.

Wundt, *A*, 4te Aufl., II., 132 ff.; Helmholtz, *A*, G. 682 ff., Fr. 695 ff. (541 ff.); Münsterberg; and the literature cited by them. For measurements of a similar kind upon squares, see Warren and Shaw (240); for measurements on circles, and for effect of color on size, see Quantz. For experiments on the exactness with which extents can be compared when their distances from the eye, and so their retinal images, are unequal, see Fechner, II., 311 f.; Martius; and v. Kries, 187 ff.

175. The Retinal Image and the Perception of Size: Ordinary Seeing. In the absence of other determining circumstances, large retinal images are taken to belong to large objects, and small to small. Undetermined cases are, however, extremely rare.

a. Known Objects are Generally Perceived as of a Constant Size, Irrespective of the Size of Their Retinal Images. Hold the hand eight inches from the face, and notice its size; then move it to sixteen inches, and observe that its apparent size remains the same, despite the fact that its retinal image has now only one-half its former length and only one-quarter its area. On further removal to twenty-four inches, the apparent size is still the same. This con-

stancy is found in estimating the height of men, domestic animals, and familiar objects generally, and is frequently made use of by painters, who introduce the figures of men and other well-known objects to suggest indirectly the size of objects near which they are placed.[1] See also Ex. 124 *d*, where a change in the size of the retinal image causes a change in the color, but not in the apparent size of the object.

b. When the objects are equally familiar, an important part is played by attention in determining which shall be taken as the measure of the other. This is easily shown with two fingers, one held at eight, the other at twenty-four inches. Steady looking at the farther finger makes the nearer look larger than normal; and looking at the nearer, makes the farther look smaller.

c. Another experiment which shows the same independence of the retinal image is cited by Helmholtz from Smith's Opticks. Place in the focus of a convex lens a wafer, a printed letter, or any other small object, and view it at different distances from the lens. As the distance increases, the object will seem to enlarge until it fills the lens completely. The fact is, however, that its image remains approximately constant in size (since the rays from it are made parallel by the lens), while the image of the lens itself, and of all other objects in the visual field, decreases in size.

Hering, *B*, 14 f; Rivers; Helmholtz, *A*, G. 839, Fr. 871 (689).

[1] In somewhat the same way a spire or tree may serve as a measure for the disk of the sun or moon rising or setting behind it, with the result that the latter seems larger than when such comparison is impossible. This, however, is by no means the only element in the illusion. The flattened form of the sky — itself the resultant of several causes — also co-operates by making the sun or moon at the horizon seem farther away, and therefore larger. The matter may be followed in Helmholtz; Aubert; Wundt; Filehne; and in a discussion by Lechalas and others in the *Revue philosophique*, juillet, 1888 - février, 1889.

176. The Retinal Image and Perceptions of Size and Distance. A circumstance that very frequently determines the apparent size of an object is its apparent distance; or, more generally, size and distance are mutually determining. If the apparent distance is constant, the apparent size of the object changes directly with the size of the retinal image; while if the apparent size is constant, the apparent distance changes inversely with the image. These are facts of very common observation. In the laboratory they may be demonstrated as follows: —

Look at a portion of a page of print through an ordinary magnifying-glass, holding the glass near the page, so that a good deal of the latter can be seen outside the lens. The retinal image of the part seen through the lens is enlarged, but the parts of the page seen outside the lens fix the distance for the whole, so that the letters seem enlarged. On the contrary, when an opera-glass or a telescope is used for a distant object, the eye is brought so close to the eye-piece that nearly all the visual field, except that seen through the instrument, is cut off. The result is, then, that objects appear nearer, and but little, if any, larger. The effect is equally clear when the retinal images are reduced by using a double concave lens in the first case, and by looking through the opera-glasses from the big end in the second.

Hillebrand, *B*, 121 f.

Perception of the Position and Movement of the Lines of Regard. The importance of eye-movements in space perception is clear from previous experiments, and will be still further emphasized by several of the Geometrical Illusions below; but the manner in which they play their part is anything but clear. It has generally been assumed that they give rise to kinæsthetic sensations of some kind.

and that through these the changing positions of the eyes are perceived. This, however, is doubtful, for direct experiment shows that perception of the positions of the eyes when retinal sensations are excluded is very defective. (Cf. Hering, *B*, 30 ff.) This has already been noticed in the case of eye-movements from dizziness (Ex. 50), and other cases are given below. What the true explanation is — whether eye-movements are effective solely by the changes they cause in the retinal impressions, or by some more direct means — is something yet to be settled.

Perception of the position of the eyes or of the lines of regard may be *absolute* or *relative*. It is obvious that perception of the absolute position can only mean the co-ordination of that perception with those of some other sense or senses, and the term is used here with that meaning only. Perception of the relative position will mean co-ordination with other perceptions of the same sense. Relative direction in the field of regard, for example, is measured from the primary position of the lines of regard, which is practically that taken by those lines when the head is erect and the eyes are fixed on the horizon.

177. Normal and Forced Movements of the Eyes. When the line of sight is shifted voluntarily, objects seen appear at rest, and the eye, so far as it is regarded, in motion. When, however, the shifting is involuntary, as when the eyes are forced to move by pressure of the fingers, or by inner causes, as in dizziness or dropping to sleep, objects seem to move. Close one eye, and take between the thumb and finger a fold of the skin at the outer edge of the orbit of the other eye, and draw it gently outward. The eye itself is thus drawn slightly in the same direction. Objects in the field seem to move a little in the opposite direction. Get a strong after-image of the window in one

eye, close and cover the same eye, and repeat the traction of the skin on that side. The after-image will not appear to move.[1]

Such a result appears to exclude sensations from change in the eye muscles, and, indeed, from any other external change in the eye from participation in any of the finer spatial perceptions.

Helmholtz, *A*, G. 743, Fr. 763 f. (600).

178. Fixation in Complete Darkness. It is difficult, if not impossible, to hold the eyes in a given position without the assistance of the retinal sensations. Arrange the dark box for binocular vision, and insert at the back a slide with a single hole. Fasten over the hole a bit of black cardboard, so as to exclude all light. Make a small pin-hole in the card, which will appear, when seen from the front, as a minute point of light. Provide, also, another piece of black cardboard, which can be used from time to time to cover the hole and cut off its light. Bring the eyes into position, and fixate the pin-hole for a second or two; then cut off its light, and try to maintain the fixation. After ten or twenty seconds allow it to appear again, and notice whether it comes at the point expected. Generally it does not. If the kinæsthetic sensations of the eyes were acute, such errors ought not to occur. For other instances of unperceived movements of the eyes, see the experiments on illusions of movement, below.

Hillebrand, *B*, 150; Helmholtz, *A*, G. 757 f., Fr. 779 f. (613).

179. False Location of After-Images.

a. If one fixates for a few seconds a small gas-flame or other bright object in a darkened room, and then, keeping

[1] It is probable that moving of the eye through a great enough angle in this way would cause some apparent movement of the after-image; such, at least, is the case when the eyes are moved involuntarily in dizziness.

his head unmoved, looks quickly away, he will observe a long positive after-image streak connecting the flame with the new fixation point. This has already been used in Ex. 132 as a means of studying the movements of the eyes. It sometimes happens, however — especially when the head is moved with the eyes, and the movement is sudden — that the after-image is not correctly located, but referred to the side of the flame opposite to that on which the new fixation point is found. It often seems to shoot out, as it were, from the flame. If the movement has been upward, the after-image seems to lie below the flame; if downward, above the flame, and similarly with other directions. As Mach expresses it, the image appears with the place-marks that belong to the old and not to the new position of the eyes. Lesser degrees of false location, in which the after-image streak is partly on the same side of the flame as the movement, and partly on the other, are also observed; and somewhat similar effects are to be seen when the movement is toward the flame from some other fixation point.

The explanations offered for the phenomenon do not seem entirely satisfactory, but the essential factor is probably defective perception of the actual movements of the eyes.

b. Lagging of the Eye when the Head is Turned. Fixate a flame or other bright object for a single second or less; then close the eyes, and quickly turn the head 30° or 40° to the right or left, or up or down. The after-image (often positive) will appear in the original direction of the object. Repeat the fixation, continuing it this time for twenty seconds. The after-image (negative) will appear to turn with the head. Intermediate positions also will sometimes be noticed. Münsterberg and Campbell report that many persons are unsuccessful in getting this result.

On *a*, Mach, *A*; Lipps, *A*. On *b*, Münsterberg and Campbell.

180. Locations in the Indirect Field of Regard.

a. Use the campimeter, adjusting the head-rest about 20 cm. from the vertical plane. Make a distinct fixation mark before the eye, and another at a distance of 15 to 18 cm. to the right or left. Let the subject bring both his hands into symmetrical positions near the median plane — e.g., on either side of the foot of the head-rest — and close his eyes. At command, let him open his eyes, take a careful observation of the distance of the side fixation mark from the median one, close his eyes again, and try to touch the side mark by a rather quick movement of the hand upon the same side. Note the extent and direction of the error, and repeat the experiment, being careful always that the subject does not shift his head, and that he keeps his eyes closed, except when judging the separation of the marks; this last, in order that he may remain in ignorance of the extent of his error. Try several times on either side. The subject will generally overestimate.

b. Repeat the experiment, this time turning the head with the eyes, instead of the eyes alone, and keeping the head turned during the touching, the eyes of course being closed as before. Also, with the head straight, try touching the median fixation mark. In both cases the error will be small or absent, showing that the defect is visual (eye-muscles), and not in the arm. Loeb finds a similar error in touching points in the peripheral field of vision; i.e., points seen indirectly without eye-movements.

Loeb's explanation is that the eye-muscles are less and less responsive, and require a greater and greater innervational discharge for a given response as they become more and more contracted. The position of the eyes (and the location of the fixation mark) is judged by the "volitional impulse" required, and therefore overestimated. For a similar tendency to overestimate the position of the eye, see Hering, *A*, 444. Cf. also Ex. 36.

On *a* and *b*, Loeb, *B*, 21 ff. On *b*, Bowditch and Southard (quantitative results for touching under various conditions); Exner, 322.

181. Co-ordination of Vision and Touch. In the ordinary use of the eyes the visual and tactual locations of objects coincide very well for direct vision. It is easy, however, to produce a dislocation of one with reference to the other, and eventually a new adjustment.

Lay on the table, at a convenient distance, a button or other small object. Observe the button for a second or two through a prism of 10–20° angle, then close the eye and attempt to touch the button by a rapid movement of the hand. The hand will be found to have erred on the side toward which the field has been shifted by the prism. A few trials with the eye open will enable the observer to touch the button with certainty. Continue the practice, however, for a few moments. Then remove the prism, observe the button with free eyes; close them, and try again to touch the button by a rapid hand-movement. An error will again be found, but in the opposite direction, showing that a new co-ordination of visual and touch space has been formed.

Helmholtz, *A*, G. 745; Fr. 765 f. (601 f.).

182. Perception of Depth by Means of Accommodation. Whether the direct muscular effort of accommodation has any effect, apart from changes of the retinal image or associated tendencies to binocular convergence of the lines of sight, has been questioned. The whole problem, both as to judgments depending on normal accommodation and on that required by chromatic aberration, is still *sub judice*, and will not be followed further here.[1]

[1] Experiments have been made on the matter by Wundt (*A*, 4te Aufl., II., 107; *B*, 105 ff.), by Hillebrand, Dixon, Rouse, Arrer, and Bourdon. For influence of chromatic aberration see Thompson, *A*; but his results are hard to verify.

That changes in accommodation cause changes in apparent size and distance has, however, long been known. If, while attention is given to a distant object, e. g., a house or tree, the eye is quickly accommodated for a near point, the distant object will appear to withdraw and diminish in size. If the operator is not able to accommodate voluntarily, the experiment may easily be made by letting him stand close to the window and select a spot on the glass for a point of near fixation. Aubert finds a difference in result with objects of unknown size. These are reduced in size, and given an extremely near location. Accommodation for a near point, while looking through a pin-hole in a card held close before the eye, shows the same result somewhat more easily, but heightened perhaps by other conditions. Carrying the card toward the object produces still further diminution in size. Aubert finds a change of apparent distance due to the efforts of accommodation when no actual change in accommodation results.

Helmholtz, *A*, G. 119; Fr. 127 (97); Aubert, *A*, 601–602, 627; Stevens, *B*, 346 f.; Kirschmann, 452; Rivers.

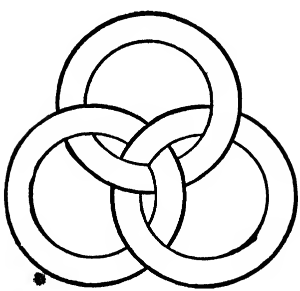
183. Perception of Depth by Means of Intervening Objects.

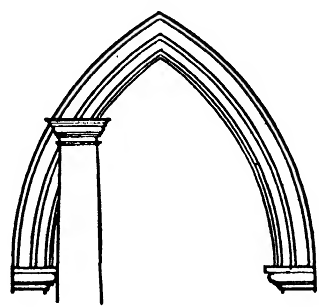
a. Several of the monocular criteria of distance are better observed in the casual use of the eyes than in specific experiments, and this among the rest. The following figures, however, show something of the tendency. We are more inclined to regard the rings in *A* as complete and interlaced than as broken and carefully laid together. In the second figure the effect is still stronger, because it is still more difficult to conceive the arch in the same plane with the column and fitting exactly into its irregular outline.

The multitude of objects intervening between the eye and the horizon, together with their known size and dis-

tance, doubtless contributes also to the flattened appearance of the dome of the sky.

b. Most people have great difficulty in seeing the image produced by a concave mirror in front of the mirror-surface, though in most cases it is actually so located. The apparent interference of intervening objects combines with the customary location of mirror-images behind the mirror-surface to produce the false location. The experiment may be made as follows: At a distance in front of a concave mirror, somewhat less than double its focal distance, is set

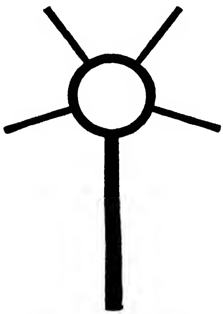




B

up a figure like that below, cut from cardboard and blackened on both sides, or even an ordinary retort ring of small size. The observer takes his position still further from the mirror in the line passing through its centre and the centre of the ring, and, if the adjustments are correct, sees floating in the air, a few inches in front of the actual figure, an enlarged and inverted image of it, so long, at least, as he observes with both eyes. The instant, however, that he looks with a single eye, the image drops back to the mirror surface or beyond. The rays of the figure, the spots on the mirror, which are plainly seen through the floating

image, and the frame of the mirror, which cuts the image off at the sides, all conspire to make the image seem behind instead of in front. If the observer has difficulty in getting the binocular location, a little swaying of the head from side to side, which causes the image to shift with reference to the mirror and the figure, may be helpful.



A similar experiment may be made with a suitably adjusted convex lens.

Helmholtz, *A*, G. 768 f.; Fr. 793 (624 f.); Sully, 80 f.

184. Perception of Relief by Means of Shadows.

a. The effect of shadows is finely shown by a mask colored alike within and without. Place the mask, with the hollow side toward the observer, in such a position that the light falls full upon it and no shadows are cast inside it. Let the observer regard it with a single eye from a distance of six or eight yards. He will find it difficult, or even impossible, to see the mask in its true concave condition, preponderant experience apparently dictating the opposite result in perception. If, however, the position of the mask is so changed that the light falls into it obliquely, the shadows immediately betray the concavity, and no difficulty is found, except, perhaps, with the nose, which lies wholly in the shadow.

Medallions with heads in low relief, when lighted equally from all sides, can with a little effort be seen either convex or concave, — cameo or intaglio. The presence of unequal illumination and cross shadows makes this more difficult. A sheet of paper folded like a half-open book, and set up vertically, shows somewhat the same effect, especially if

the lower end is covered so that its contact with the table cannot be seen. Cf. Fig. *N*, Ex. 202 and Ex. 203.

b. Waller's Experiment. In the following experiment dark borders resembling shadows lead to an illusion of elevation or depression. Cut a piece of cardboard eight inches long by four wide; cover half of it smoothly with red paper and half with blue. On the red paper paste several strips of blue, and on the blue several strips of red, strips a quarter of an inch wide by two long; or, better, put on concentric rings of the specified colors, leaving spaces between at least equal to the breadth of the rings. The gummed rings used by kindergartners serve excellently for the purpose. Place the diagram thus made in such a position that it shall be strongly illuminated from the right side, and view it from a distance of two or three yards with a single eye, covering half the pupil with a bit of black cardboard, or, better, through a hole in the cardboard about two mm. square, the card being shifted toward the nose or the temple to imitate a similar dislocation of the pupil.

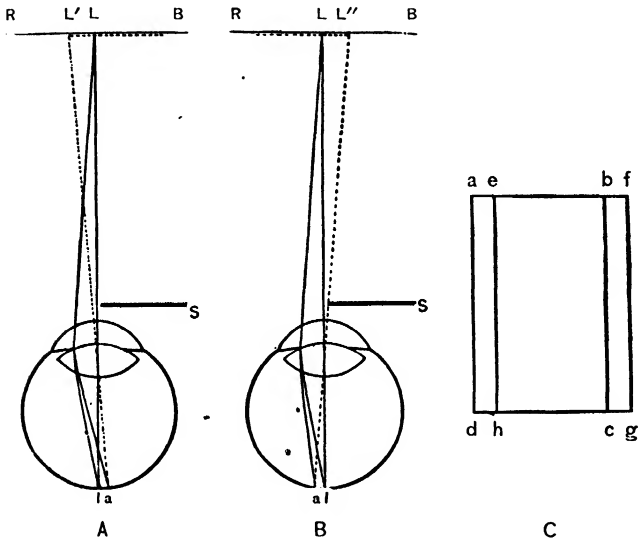
If the temporal half of the right pupil is covered, the red rings will appear to stand out slightly from their ground; the blue will appear to lie somewhat depressed in theirs. If the nasal half of the pupil is covered, the red will be depressed and the blue elevated. The same is true for the left eye if the terms nasal and temporal are interchanged. Notice in each case the apparent distribution of light and shade. Changing the direction of illumination sometimes reverses the phenomenon. The experiment may be somewhat easier when the observer looks through a piece of blue glass (or violet or purple gelatine) held close before the eye. The purpose of the blue glass is simply to make the blue and red of the papers used in the diagram purer. The edge of the card that covers the pupil may be black-

ened with advantage, and slight movements of the card may also prove helpful.

The illusion depends upon the interpretation of the apparent shadows and high lights. These arise from chromatic aberration, which is made much more apparent than in the normal eye by half-covering the pupil. The matter will be made clear by an examination of the figures opposite. In discussing the figures, it is assumed that the colors in question are perfectly pure, and that the right eye is taken for experiment, with the temporal half of the pupil covered.

It is impossible to accommodate the eye at the same time for both red and blue; if the red rays are brought to a focus on the retina, the blue rays are focused in front of it; if the blue rays are brought to a focus on the retina, the red rays are focused behind it. In the figures opposite, *L* represents the line of demarcation between a red area and a blue area; in Fig. *A* the eye is accommodated for the red; in *B* for the blue. In *A* the edge of the red in the retinal image lies at *l*, the edge of the blue at *a*, which, when referred outward on the line of direction *a L'*, locates the blue edge at *L'*, a shifting toward the left, which causes an over-lapping of the red and blue, since the red edge is perceived at *L* in its true position. Similarly in Fig. *B* accommodation for the blue causes an apparent shifting of the location of the edge of the red to *L''*, a shifting toward the right. Any intermediate degree of accommodation would cause a shifting of both the red and the blue in opposite directions. In Fig. *C* is also shown another result of such shiftings. Assume that *a b c d* represents a red strip on a blue ground. When this combination is viewed with the temporal half of the right pupil covered, there is a mutual shifting of the colors, and the strip *a b c d* appears in the position *e f g h*. The result is a summation of the colors in the region *b f g c*, and an absence of all

color (darkness) in the area *a e h d*. The region of summation is taken as a high light, the region of darkness as a shadow — a condition of things that would be exactly paralleled if a slight elevation existed in a field illuminated obliquely from the right.[1] In a way entirely similar to



that just used, the cases of blue figures on a red ground, of vision with the nasal half of the pupil covered, and of vision with the left eye, can readily be explained.

On *a*, Helmholtz, *A*, G. 772; Fr. 797 f (628); Bowditch; Oppel, *B*. On *b*, Einthoven. Brewster.

[1] Einthoven, who has investigated this phenomenon carefully with a nearly identical setting of the experiment, considers the direction of illumination of little consequence. In the setting here used, it has seemed to me rather important, though not absolutely determining. The illusion is one of perceptive interpretation, where individual differences are to be expected. The main point remains, however, in either case, that illusory shadows cause a plastic interpretation of the figure.

185. Perception of Relief as Influenced by Other Perceptions and Ideas. Lay on the table a short strip of paper torn roughly across one end. Look with a single eye at the paper through a convex lens of short focus, from a distance of two or three feet, in such a way that the line of sight makes an angle of about 45° with the surface of the table. The lens will present an inverted image of the strip. This image, if exactly perceived, ought to appear vertical, or nearly so; it will seem, however, nearly horizontal, and the end which is actually farther away will seem the nearer. It will be found advantageous to have the image of the paper nearly fill the lens. Repeat the experiment, this time sticking a pin vertically into the paper. This will favor a truer perception of the position of the image. The false location of the paper depends on the pre-conception that the table surface, as seen through the lens, still belongs to the rest of the surface as seen outside of the lens and known by sight and touch. To harmonize with this the paper must seem turned end for end. With the aid of the pin, it takes a vertical position, and the end which is actually nearer seems so still.

When figures in shallow relief are thus viewed, they will also seem horizontal, if little or nothing of their surroundings is seen at the same time, and often show changes from depression to elevation or *vice versa*. If they assume the vertical position their relief is seen correctly. The changes depend somewhat on the object represented, medallions easily changing from intaglio to cameo form, but not so readily from cameo to intaglio. Shadows are very important here, and their effect can be finely shown when such figures are tried by artificial light. Cf. Ex. 203.

Helmholtz, *A*, G. 773; Fr. 798 (628); Brewster, *B*.

186. The Perception of Form and Distance in Inverted Pictures and with Inverted Head.

a. Form and Distance in Inverted Pictures. Pictures produce a decidedly different effect when examined upside down. Try with any convenient set of pictures, including both portraits and landscapes. The effect of inversion is strikingly shown in the "topsy-turvy" picture books common a year or two ago, and is true to a certain extent even of familiar portraits. In inverted landscapes, besides the general strangeness and a strong tendency to take sky for water and *vice versa*, there is often an imperfect perception of distance which results, when the picture is righted, in an apparent retreat of objects in the background. This is due, in the opinion of Filehne, to our vastly preponderant experience in the recognition of perspective effects on the ground and below the horizon line.[1] In the inverted picture, lines that usually converge upward converge downward, and only suggest imperfectly their usual interpretation. Dr. Margaret Washburn finds many cases of a reverse effect, the background seeming at a greater distance in the inverted position, and suggests in explanation a different estimate of size in the upper and lower parts of the field, similar to that in the case of the geometrical illusions of Ex. 196, below.

b. Distance with Inverted Head. When the actual landscape is viewed with inverted head, by looking under the arm or between the legs, the appearance of things is considerably changed; the movements of men and animals seem unfamiliar, colors are often brightened, and illusions with regard to distance are experienced.

Try the experiment, taking pains to have the eyes at the same height above the ground in both the inverted and erect positions. If this last is not regarded, an increase

[1] Filehne also uses the same principle for explaining the flattened shape of sky and the enlargement of the moon at the horizon.

of distance in the inverted position and a decrease in the erect will be observed which is not directly due to the inversion of the head.

The apparent changes in color result from a change in interpretation. In the erect position colors are attended to as signs of objects of certain qualities at certain distances. In the inverted position the perception of the latter element is less perfect, and the colors are seen more independently.

The nature of the distance illusion has been differently reported by different observers. Helmholtz and others see distant objects as more distant with the head erect; James sees them nearer. Dr. Washburn's tests with pictures makes it probable that more than a single factor may enter at times, and the result with different landscapes may be different.[1] My own trials suggest that with complicated expanses like a view of city roofs and buildings, which is poorly disentangled with the head inverted, the normal position gives the greater distance; while with a simple and relatively unbroken expanse the reverse may be the case.

On *a*, Mach, *A*, 50; Filehne, 300 f.; Hering, *A*, 571. On *b*, Helmholtz, *A*, G. 607, 871 ff.; Fr. 568 f., 913, 915 (433, 723, 725); Rood; James, II., 213; Margaret Washburn; Filehne, 297 ff.; Thiéry, 102.

Geometrical Illusions.

Beside the illusions just considered, a large number have been found that affect the perception of plane figures. In some of these the effect of perspective or the tendency to interpret the lines as representations of three-dimensional

[1] Professor James does not say explicitly that he and his observers were careful about keeping the eye the same height above the ground in the two cases. If this was not regarded it might account for the difference in his result.

figures is clear; in others the influence of preponderating experience, or of eye-movements, is to be observed. It is probable that many, even of those that seem most simple, are the resultant of several simultaneous tendencies; considerable individual differences in the extent of these illusions may therefore be looked for. A full treatment is out of the question here, the brief commentary on the diagrams being intended merely as a suggestion of the views held with regard to them, not as an exposition or criticism of those views. The student will do well to turn the diagrams about and to view them from different sides, so as to separate the illusions that depend on position from those that do not. In general, illusions are strengthened when the affected lines are made oblique in the field. For very exact and careful study the diagrams should be separated from one another and from the influence of all extraneous lines, e. g., drawn singly on good sized sheets of paper. Sometimes the size of the diagrams makes a difference, some illusions being more striking in large figures, others in small. The figures in the text are not to be taken as standards in this regard. Many illusions are much intensified when the figures are drawn on glass, or made of wire as actual models, especially when their parts are movable, and the extent or place of the illusory effect can be changed before the eyes of the observer. Many of the figures in Bradley's "Pseudoptics" possess this advantage.[1]

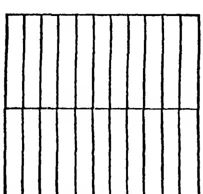
[1] It has often seemed to the writer that many illusions showed more strongly in rough drawings on the blackboard or on paper, even when the figures were so made as to throw the unavoidable inaccuracies against the illusory effect, than in the more rigid diagrams of the books. If this is a fact it might be due in part to something similar to that just mentioned — the actual change of the figure in construction, — and in part to the greater share of apperception in such rough diagrams.

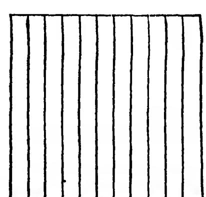
For illusions depending on irradiation, see Chap. VIII.

On the Geometrical Illusion in general, see Wundt, *A*, 4te Aufl., II., 137-156; Helmholtz, *A*, G. 705 ff.; F. 720 ff. (562 ff.); Hoppe, *A*; Lipps, and Thiéry.

187. The Tendency of the Eye to Follow Lines and Contours. The most important thing in ordinary seeing is a clear perception of form, and lines and contours are followed because they are the best key to that perception. Lines that are followed by the eye (Wundt's *Fixation Lines*) are more clearly seen than those that are not, and lines lying nearly in the same direction as those that are followed are favored above those in other directions. It is easy to see that this habit of the eyes must play a great rôle in the geometrical illusions. This tendency is, however, not beyond conscious control, and for that reason is more difficult to demonstrate by overt experimentation than by casual observation. Any one who will take note of his own seeing when presented with objects with strongly marked lines, will easily find trace of the habit. In imagining geometrical figures also (for example, an eighteen-inch hexagon) something of the same tendency will often be found.

a. Let the observer examine the figure below for a moment, and then require him to say how his eyes have moved in doing so.





He will probably find a tendency to follow the middle line of the left figure, and the vertical lines of the right.

b. Paste upon a piece of cardboard eight and one-eighth inches long and four inches wide, two four-inch squares of

red paper in such a way as to cover all the card except a white stripe one-eighth of an inch wide between them. Cover the whole with a sheet of semi-transparent paper, as for Meyer's experiment (Ex. 152 *c*), and examine the white stripe for the effects of contrast. After the examination has lasted a few seconds, suddenly lay across the middle of the diagram a bit of wire six or eight inches long, at right angles to the white stripe. If the experiment succeeds, the white stripe will instantly show a strong increase in the complementary color. Before the introduction of the wire, the eye is chiefly engaged in following up and down the white stripe, and the contrast effects are confined to those of simultaneous contrast. When the wire appears, the eye changes to it and moves back and forth along it once or twice, and thus brings upon the white stripe the more powerful effects of successive contrast.[1]

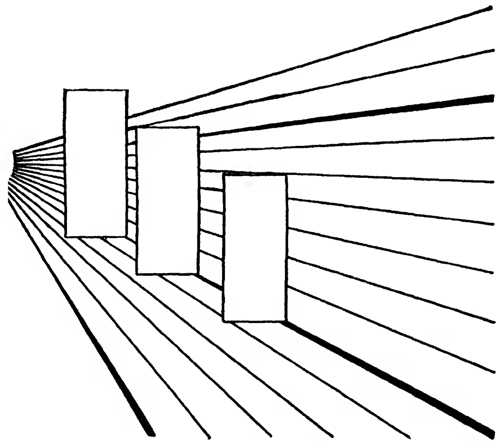
Thiéry, 112; Waller.

188. Perspective Figures. The tendency to see things spatially is so inveterate that a moderate suggestion of perspective is sufficient to introduce differences in apparent distance and so of apparent size.

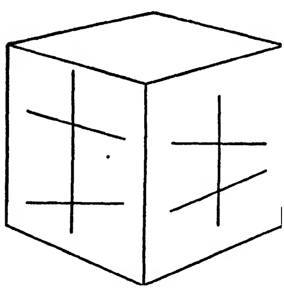
a. Von Bezold's Figure. The following figure, after von Bezold, shows the tendency in question sufficiently well.

It is interesting to observe that the enlargement of the remoter figures is not so great as the represented distance would require — that is, the perspective interpretation is not effective in full measure. A good example of this figure will be found in Bradley's "Pseudoptics." It has also been used in advertising.

[1] This experiment originates with Waller (*Journal of Physiology*, XII., 4, p. xliv.), but is used by him for a different purpose.



b. Under favorable circumstances the perspective illusion may cause an apparent distortion of an actual right angle.



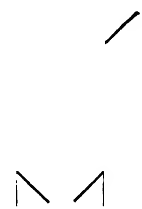
This is the case with the lower cross on the left of the cube, and the upper cross on the right. The rectangularity of the crosses is lost when the perspective impression is strong, and *vice versa.* The same effect may also be observed when the after-image of a rectangular cross is projected upon a drawing of a cube. Cf. the distortion of the rectangular after-image in Ex. 131 *b* (p. 124).

On *a*, von Bezold, *B* ; on *b*, James, II., 254 ; Thiéry, 317.

189. Perspective Interpretation of Plane Figures. Certain arrangements of lines tend, upon very slight suggestion, or even without it, to take on a three-dimensional

interpretation. This may happen with oblique lines in drawings on paper, but is easier to observe with wire models or figures drawn upon glass, where there is less to favor a plane interpretation, and with monocular rather than binocular vision.

Prepare models or figures on glass similar to those below, place them in such a position that they may be observed against the sky or other uniform background, and observe with a single eye.



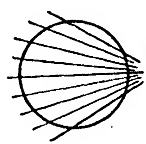
The tendency to a three-dimensional interpretation is stronger in *A* and *B* than in *C* and *D*. In *A* and *B* it is the oblique lines, not the vertical and horizontal that are affected, at least to an appreciable degree. *E* is only a reduplication of *A*, but the perspective interpretation of the short lines also involves a slight inclination of the verticals. The figures are almost all capable of two perspective interpretations; in *A*, for example, the lower end of the oblique line may be nearer than the vertical or farther away. (Cf. the Equivocal Figures of Exs. 201–203.)

This tendency to perceive oblique angles as perspective pictures of right angles is perhaps connected with the tendency to overestimate small angles, and underestimate

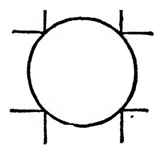
large ones, long familiar to those who have busied themselves with the geometrical illusions. (Cf. Ex. 190.)

Hering, *A*, 579 f., *B*, 79 f.; Mach, *A*, 96 ff.

190. Illusions in the Perception of Angles. Small angles are relatively overestimated, and large angles relatively underestimated.[1]



D



In *A* and *B* slight distortions are found in the horizontal lines. In *C* the circle is flattened at the corners of the square, and the sides of the latter are bent inward. In *D*, the distortion is unmistakable, but probably not due to the small angles alone. (Cf. Exs. 192 and 195.) *E* seems at first to contradict the principle of the overestimation of small angles, for the effect is the same in kind as in *C*, when the reverse effect might have been expected. But Thiéry is probably right in saying (366 ff.) that the important condition of eye-movements is different in the two cases. In *C* the eye-movement seems to follow the chord or the arc — in either case it is such that the eye meets lines which make a small angle with the one along which it

[1] Jastrow (*A*, 382) considers that all angles are underestimated, both acute and obtuse, but the obtuse much more than the acute, so that when both occur together, as they commonly do, the effect is equivalent to an overestimation of the small.

moves. In *E*, however, when the eye moves along one of the short lines toward the circle it tends to follow on along the arc that would require the least change of direction, that is, the one with which it makes an obtuse angle. If this is the case, the illusion is one of obtuse instead of acute angles, and the result is in accord with the principle.

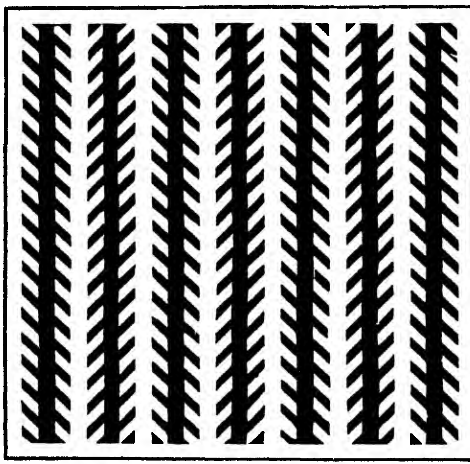
The general case of the overestimation of small angles Wundt refers to eye-movements as influenced by adjacent lines. In *A*, for example, as the eye follows the horizontal line toward its intersection with the oblique lines, it suffers, as it were, an increasing attraction toward the oblique line nearest it, and from this results the wrong conception of its route. In explanation of the first three figures, Helmholtz cites his principle "according to which acute angles, being small magnitudes clearly limited, seem in general relatively too large, when we compare them with undivided obtuse or right angles," but believes that this principle yields in importance to ocular movements, if, indeed, it does not itself depend on them. — *A*, G. 708 ff.; Fr. 724 ff. (566 ff.). The explanation of this illusion by the tendency to see oblique angles as right angles in perspective has already been mentioned.

Thiéry, 360 ff.; Wundt, *A*, 4te Aufl., II., 145 ff.; Helmholtz, *A*, G. 707 ff.; Fr. 722 ff. (564 ff.); Hering, *A*, 372 f.; Mach, *A*, 98; Delbœuf, *A*; Dresslar.

191. Zöllner's Figure.

a. In this well-known figure the vertical lines, though actually parallel, appear to converge alternately above and below. They may also show, slightly, the same tendency to leave the plane of the paper that is sometimes noticed in the long lines of *E*, Ex. 189, of which this figure is simply an elaboration. The short lines also show the illusion of Poggendorff (Ex. 193).

b. The illusion is considerably increased when the eyes move across the diagram at right angles to the long lines; it is diminished or abolished when they move in the same direction as the long lines. The easiest way of securing definite movement of the eyes in these directions is to



fixate the head of a pin moved to and fro across the diagram, or to move the figure to and fro behind the fixated pin-head. A certain moderate rate of movement, easily to be found by trial, gives the best results. Continuous fixation of the pin-head is very important. The writer finds some help in bringing the diagram rather near the eye, i.e., within six or eight inches. Notice with the crosswise movement, beside the apparent running of the long lines upward and downward (which will be considered in the section on the visual perception of motion), their inclination with reference to the plane of the paper.

c. Several other points with regard to the completeness of the illusion have been observed. Most have obvious relation to changes in the movement of the eyes in traversing the figure. *Position of the diagram:* If the diagram is rotated in a plane parallel to the frontal plane of the face, the illusion is most marked when the long lines make an angle of about 45° with the vertical. It is less when these lines are vertical, and less also when they are horizontal. If the diagram be rotated backward from the plane just mentioned about an axis parallel to a line connecting the centres of the eyes, the illusion will be decreased if the long lines have been vertical at the start, and increased if they have been horizontal. *The size and distance of the diagram* seem to affect the extent of the illusion. (Kundt, 121, 148 ff.) *Transversals:* The illusion is usually stronger when the transversals make an angle of about 30° with the long lines, but may reach a maximum at a smaller angle when the transversals are long. (Heymans.) It is said to increase with the number of transversals up to a certain number, but then to decrease. *Monocular Vision* has been found more favorable than binocular, and wandering of the eyes than steady fixation. On several of these and on other points Zöllner, Kundt, Thiéry, and Heymans have made quantitative experiments.

Explanations of the Zöllner figure are numerous. It is obviously of the small angle type, and the explanations given for the other figures of that class are applied to this one also. Helmholtz associates with the overestimation of small angles the very striking upward and downward movements of the long lines observed in experiment *b* above. Similar movements of actual objects give rise to a still stronger illusion of the same sort. (Cf. Ex. 225.) He indicates also how the whole may be treated under the general principle of contrast — here a contrast of direction.

Another explanation, originating with Volkmann[1] and supported by the observations of others, has recently been further developed by Thiéry. It is, briefly, that even in casual observation the figure is seen perspectively — not consciously, but in effect. The short, oblique lines represent planes seen in perspective, each pair of planes forming a roof-like ridge, and each ridge inclining forward or backward, as the case may be; the pair at the left of the figure, for example, form a ridge that inclines forward, the second and third one that inclines backward, the third and fourth forward, and so on. The long lines are projected on these inclined surfaces, and are therefore interpreted as converging or diverging lines, though their retinal images still remain parallel, exactly as parallel retinal images would be interpreted if they had originated from actually converging or diverging lines lying in sloping surfaces.[2] Heymans connects the figure with the illusion of Mellinghoff and Loeb (Ex. 197 *d*) and approves its tentative classification as a case of contrast, but would not exclude an ultimate reference to vividly conceived eye-movements.

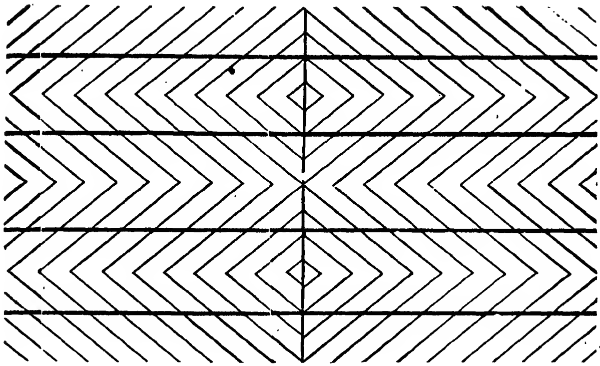
d. Variants of the Zöllner Figure.

The figures of Pisco and Hering are chiefly interesting historically. The checker-board figure, on the contrary, is important for the theory of the illusion, for it exhibits the Zöllner effect without the usual short oblique lines.[3] For the discussion of this and other figures which do the same, see Heymans, *B*.

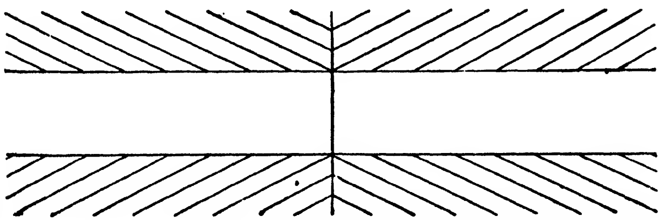
[1] Physiologische Untersuchungen im Gebiete der Optik, Leipzig, 1863, S. 163. cited by Hering, *A*, 580.

[2] That no such inclination of the planes is seen by the observer until it is suggested to him is fully recognized and even insisted upon by Thiéry. It is no more necessary, however, that the perspective factor should be conscious in order that it may influence the final form of the perception than that the partial tones in a note on a violin should be consciously recognized before it can be distinguished from a note of the same pitch on a flute. Cf. Thiéry, 121 ff.

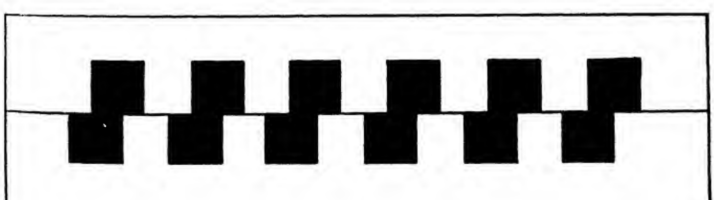
[3] See Notes and Suggestions, p. 435.



Pisco's Figure.



One of Hering's Variants of the Zollner Figure.[1]



Checker-board Figure.

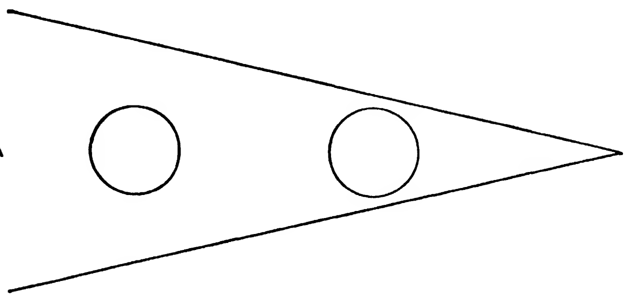
Helmholtz, *A*, G. 708 ff. ; Fr. 723 ff. (565 ff.) ; Hering, *A*, 373, 579, *B*, 75 f., 78 ff. ; Aubert, *A*, 630 f ; Mach *A*, 98 ; Wundt, *A*, 4te Aufl., II., 144 ff. ; Zöllner, *A* and *B* ; Lipps, *B*, 267 ff. ; Heymans, *B* ; Jastrow, *A* ; Thiéry, 312 ff., and the literature cited by them.

[1] By permission, from Ladd's "Elements of Physiological Psychology" (Copyright, 1887, by Charles Scribner's Sons).

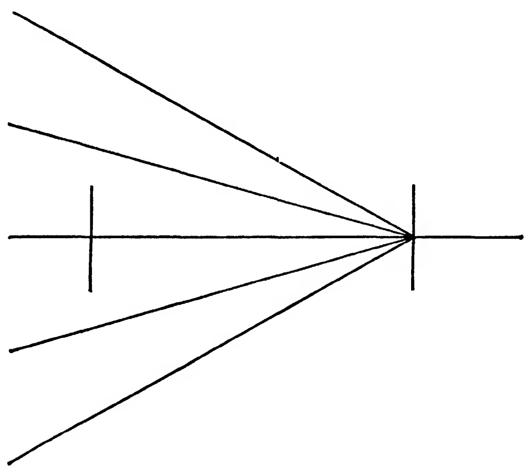
192. Figures Based on Convergent Lines.[1]

a. In *A* the circles are of equal size, but that next the vertex of the angle seems a little larger. When such a figure is made on glass the apparent difference in size may

A



B

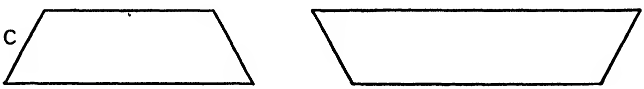


[1] In many of these figures, though there is little or no conscious tendency to a three-dimensional interpretation, the lines resemble those of perspective drawings, and the illusions are similar in character. How far the illusion in any case is due to perspective suggestion cannot now be said. In the figures of paragraph *b*, it can hardly be detected; in those of *a* and *c*, it seems to be present. If a distinctive name were desired for such figures, they might be called *Perspectiform Figures.*

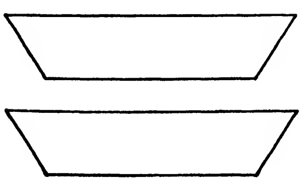
bring about an apparent difference in distance, the circle lying most remote from the apex of the angle seeming to lie farther back. In *B* the short verticals are of equal length, but that at the left seems slightly shorter. For the writer this illusion is rather weak and evanescent. Such effects are frequent with converging lines. For quantitative experiments on this illusion see Thiéry, 607 ff.

b. Trapezoids. In trapezoids the short side is overestimated and the long side underestimated. In *C* the long

C



side of the left figure and the short side of the right figure are equal, but the latter seems a little longer. This is true also of equal spaces marked off on the longer and shorter sides (see *F* below), but for this last another factor may be partly responsible. (Cf. Ex. 197.)



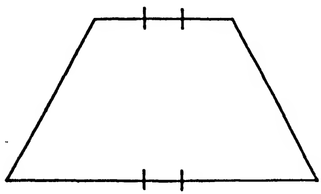
D

E

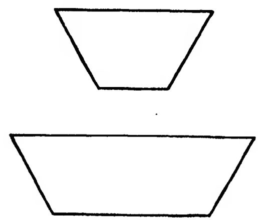
A similar effect is produced on figures lying outside the trapezoid next the short side or the long. In *D*, for example, the trapezoids are exactly alike; but the upper one (lying next the long side of the lower) seems a little smaller than the lower (lying next the short side of the upper). In *E* the same is true of the open distances

between the ends of the lines. This figure also shows a possible transition to Zöllner's figure, all that is necessary being the parallel verticals.

Figure *G* is so arranged as to add the illusion affecting the sides of the trapezoids to that depending on their po-



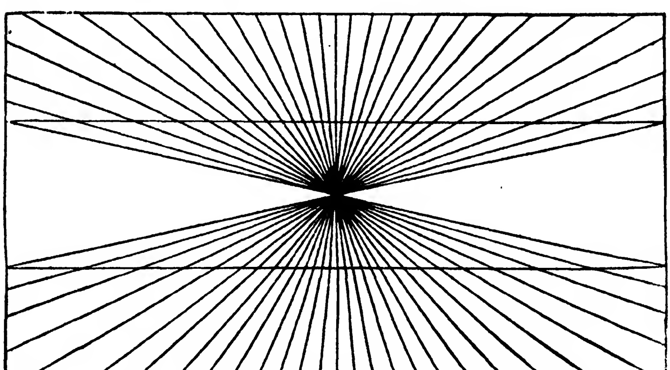
F



G

sition. The short side of the lower figure and the long side of the upper are of exactly equal length. For quantitative studies of these figures see Thiéry, 605 f., 67 ff.

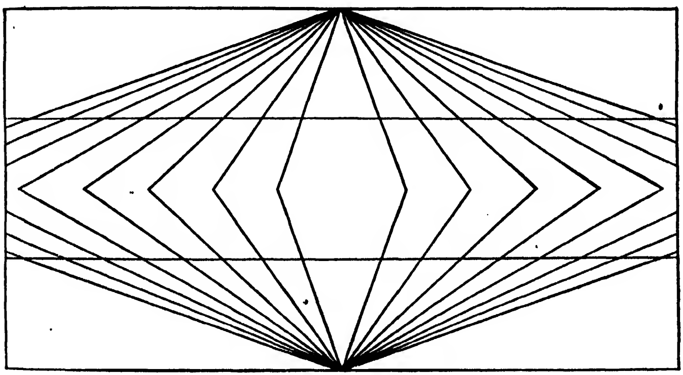
An examination of these figures shows their close relation to the Müller-Lyer figure of Ex. 194.



Hering's Figure.[1]

[1] By permission, from Ladd's "Elements of Physiological Psychology" (Copyright, 1887, by Charles Scribner's Sons).

c. In the two figures shown here the perspective suggestion is sometimes quite strong, the points of convergence seeming to lie far in the background. This three-dimensional suggestion, according to Thiéry, affects the parallels also, making some parts of them seem more remote than others, and so leading in those parts to overestimation of their separation. It is evident, however, that the figures can be classed with the small angle group, and the cause of



Wundt's Figure.

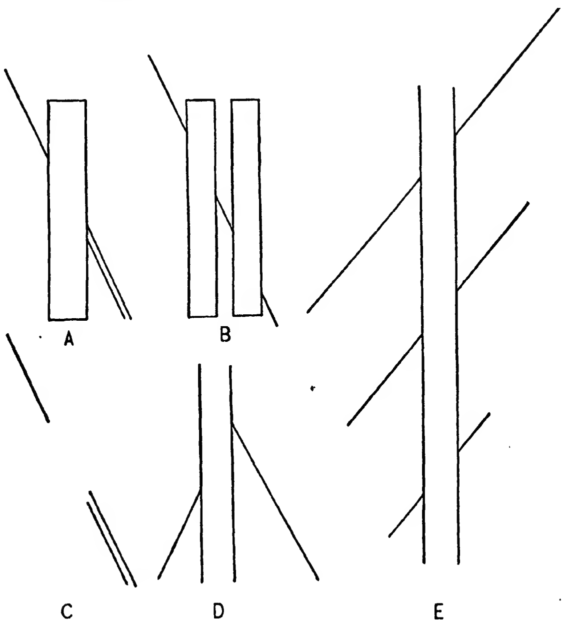
that illusion may be responsible in large measure for the distortions in this case. Cf. also Müller-Lyer's figure, Ex. 194 *a*.

On *a*, Holtz ; Thiéry, 607 ff. On *b*, Müller-Lyer, *A*, 269 f. ; Thiéry, 605 f., 67 ff. On *c*, Hering, *B*, 74 ; Thiéry, 74 f.

193. Poggendorff's Illusion.

In the typical figure for this illusion, *A* below, the line on the left is the real continuation of the lower line at the right, and not of the upper, as appears to be the case. This illusion is strengthened by viewing it from a distance, i.e., by reducing the size of its retinal image. It is weakened or quite destroyed by turning the figure so that the oblique

lines are vertical or horizontal. The length of the oblique lines, the angle at which they cut the parallels, and the separation of the parallels, are all of importance. For quantitative studies see Thiéry, 357 ff., and Burmester. In *B* the three oblique lines are all parts of one straight line, but do not appear so.[1] *C* is a figure given by Wundt to



show that the presence of an actual oblong is not necessary. The illusion in *C* is feeble, and probably is different in amount for different observers; Burmester found it entirely reversed in direction (pp. 358, 390 f.). It may even be doubted whether the illusion in this case really belongs to

[1] Figures *A* and *B* are taken by permission from Ladd's "Elements of Physiological Psychology" (Copyright, 1887, by Charles Scribner's Sons).

the Poggendorff type and is not rather a case of the Mellinghoff-Loeb figure, Ex. 197 *d*. In *D* the oblique line at the left, if prolonged, would pass through the point of intersection of the two lines at the right, but seems to lie too low. In *E* is shown the increase of the illusion with decreasing length in the oblique lines.

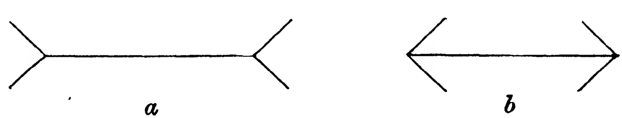
Poggendorff's figure, according to Wundt, involves several illusions. The figure is estimated too large in the direction of its prominent (vertical) lines, and in this the habitual overestimation of verticals helps. When the latter is excluded by turning the figure on its side, the illusion that remains is to be explained partly by overestimation in the direction of prominent lines, and partly by overestimation of small angles. Helmholtz suggests irradiation as a co-operating cause. Thiéry connects it with the tendency to see inclined lines perspectively, already noticed in Ex. 189.

Helmholtz, *A*, G. 707 f.; Fr. 722 f. (564 f.); Hering, *A*, 372; Wundt, *A*, 4te Aufl., II., 148; Delbœuf, *C*; Dresslar.

194. The Figure of Müller-Lyer. This is by far the most important and most discussed of recent figures.

a. The common form of the figure is given in *A*. The horizontal lines are of exactly equal length, but do not

A

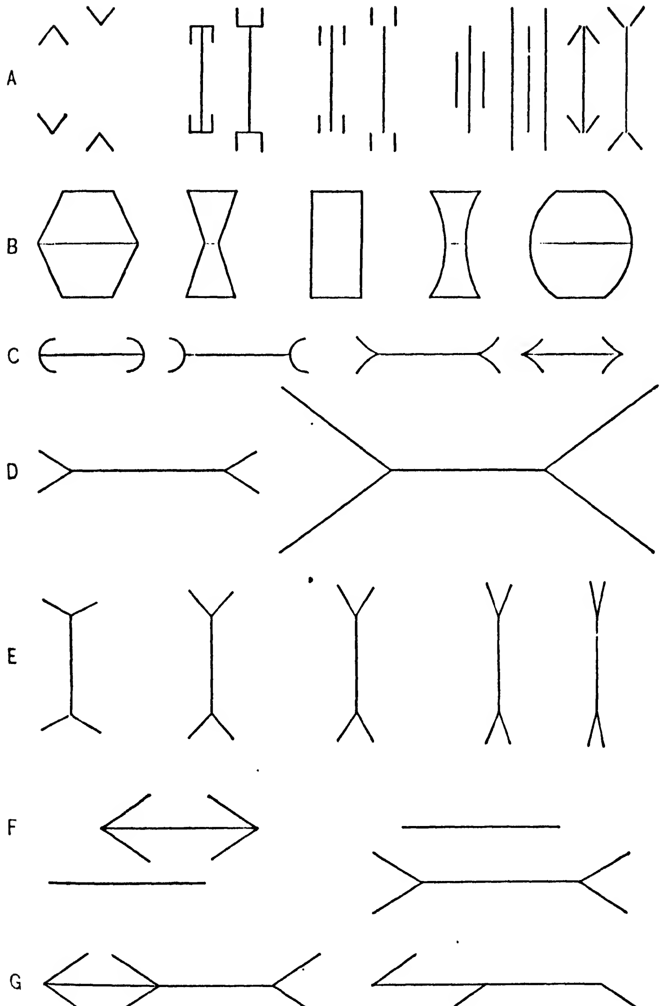


seem so. These figures are closely related to those of Ex. 192 *b*. Both *a* and *b* may be conceived as composed of two trapezoids having a side in common (the central line), and a side omitted. In *a* the short sides are common and the long omitted; in *b* the reverse. They may even be derived,

though somewhat arbitrarily, from the figures of Ex. 192 *c*; *a* may be reached from Hering's figure by extending the point of convergence into a horizontal line and reducing the converging lines to four; *b* from Wundt's figure by taking any four connected lines forming a lozenge and supplying the horizontal. Müller-Lyer himself connects the figure with the illusion affecting the apparent length of the arms of angles noticed in Ex. 199 *d*.

b. A Number of Variants of the Müller-Lyer figure are given in the accompanying cut.

The variations in *A* are intended to show that the illusion persists when the central lines are omitted; when the oblique lines do not actually touch the central lines; and, in some degree, at least, when no oblique lines are used. *B* is a group of geometrical figures, the first, second, fourth, and fifth of which involve a part of the lines of the typical figure. The upper half of the hexagon, for example, may be regarded as *a* of the typical figure with the upper oblique lines removed, and the upper half of the next figure as *b* of the typical figure treated in the same way. The central rectangle is added for purposes of comparison. In all the figures the horizontal lines at the top and bottom are equal. If the fine horizontals are taken as central lines, the first and fifth figures become examples of *b*, and the second and fourth of *a*, in the typical figure. *C* shows the illusion present when curved lines are substituted for the oblique lines of the typical figure. The figures from *D* to *G* show the effect of changes in the typical figure itself. In *D* the horizontals are equal, but the excessive lengthening of the oblique lines has weakened the illusion, — according to Müller-Lyer, because of a strong contrastive effect; cf. Ex. 197. In *E* the figures are alike, except in the angle made by the oblique lines. The angles between the obliques are approximately 120°, 90°, 60°, 30°, and 15°. In *F* all the horizontals are


A
B
C
D
E
F
G

equal, and the figures show the usual shortening and lengthening with reference to the standard lines beside them. If, however, the extent of the illusion in the two cases is regarded, it is found to be greater in the second case; i.e., in *a* of the typical figure. *G* shows, in the right-hand figure, a weakening of the illusion, due to the omission of half of the oblique lines. Quantitative studies have been made by Müller-Lyer, Auerbach, Heymans, Binet, van Biervliet, and Thiéry (73 ff.).

Explanations of the Figure of Müller-Lyer. Many explanations of this figure have been offered. Müller-Lyer himself regards the overestimation in one case, and underestimation in the other, as effects of the areas inclosed by the sloping lines above and below the horizontal. In *a* of the typical figure these are longer than the line, and cause it to seem longer; in *b* they are shorter, and cause the line also to seem shorter.[1] In the fourth figure of *A* the added parallels take the place of the spaces. Auerbach holds substantially the same opinion, and that of Jastrow is not very different.

Thiéry considers this figure an elaboration of the trapezoid, the illusion being strengthened by duplication above and below. The illusion would then be one of the perspectiform class, and the apparent difference in the length of the lines would rest ultimately on a difference of the distances to which they are (unconsciously) referred. Thiéry finds a ground for this difference of the distance factor in the different ways in which the eyes traverse the two figures.

[1] If this explanation is true, we evidently have, not a contrast effect, but its opposite — an adjuvant effect — exercised by one perceptive quantity on another. Illusions of this kind Müller-Lyer calls "Illusions of Confluence." Under other circumstances, as in Ex. 197, he considers that an actual contrast is present. In *D*, above, the confluent and contrastive tendencies are both present. In the short-armed figure they co-operate; in the long-armed, they are opposed. (Müller-Lyer, *B*, 11 ff., *C*, 423 f.)

Some of the other explanations may be mentioned still more briefly. Delbœuf and Wundt have held that the eye, in moving along the central lines, tends to follow out upon the short lines when they are outwardly directed, and to stop short of the end of the central line when they are inwardly directed. Heymans also holds an eye-movement theory, but of somewhat different form. In discussing these and other geometrical illusions, Lipps makes use of many æsthetic forms of expression, such as "liveliness," "inner activity," "upward striving," thus seeming to attribute the illusory effect to "forces" inherent in the figures. His thought is rather, however, that the illusion depends on the meaning of the figures as perceived things. Eye-movements are influential, but the conception of the figures controls them. Cf. Lipps, *B*, 284 ff. Brunot has held that these figures are like those of Ex. 199 *c*, and that we do not really estimate the distance from the apex of the short lines, but from the centre of one group of short lines to the centre of the other, as if the pair formed a triangle with an imaginary side. The skilful observer will very likely find several of these tendencies in his own study of the figure, and the explanations are, indeed, not totally exclusive of one another.

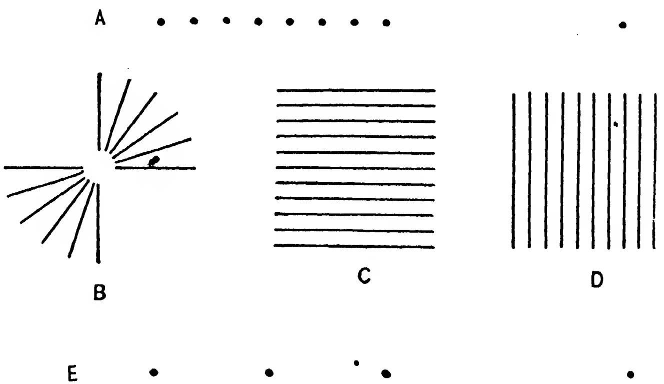
Müller-Lyer, *A*, *B*, and *C*. Jastrow, *A*, 396. Brentano. Delbœuf, *C*. Wundt, *A*, 4te Aufl., II., 149 f. Brunot; Auerbach; Heymans, *A*; Binet; Thiéry, 67 ff.; van Biervliet.

195. Illusions of Interrupted Extent.

Interrupted intervals generally seem larger than free intervals. In the first two figures above, the interrupted extents seem larger than the free extents. In *E*, however, where the interrupted space has but a single dot in the middle, the principle suffers an exception. *B* should be regarded binocularly, for monocular observation introduces

an illusion affecting the perception of the vertical. *C* and *D* are equal and square.[1]

Wundt's explanation rests on variation in eye-movements. In passing over interrupted extents, the movement of the eye is made more difficult by the short stages into which its course tends to break, while it sweeps with relative



freedom over the empty spaces. The fact that a single interruption in the middle of a space has an opposite effect, is explained by a tendency of the eye, when the middle of

[1] The illusion in these squares runs counter to the practice of dressmakers, who recommend vertical stripes as a means of increasing the apparent height. The explanation of the contradiction seems to lie in the difference of the use of the eyes in the two cases. In comparing the squares in height or breadth the eye is forced to move across the lines of one or the other, and the illusion of interrupted extent is thus introduced. In looking at a garment, however, the eye follows the most prominent lines, and tends not to cross them. In a vertically striped dress, therefore, it is the length of the vertical lines that is the chief element in perception. It is probable that in a garment with few and strongly marked transverse stripes the eye tends to move transversely rather than vertically, and the breadth of the wearer is more regarded than the height. If, however, the transverse stripes are very numerous, the eye may follow the general outlines of the figure instead of the single stripes, and an overestimate of the height again result from the interruption of the extent.

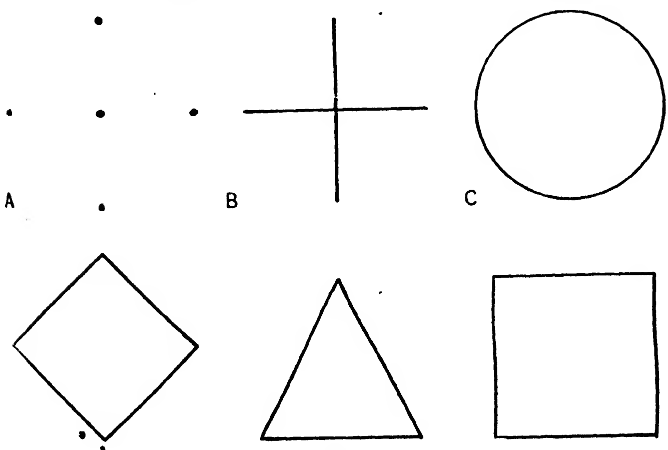
an extent is marked, to take in the extent simultaneously by fixation of the middle without motion. For other explanations see Helmholtz, *A*, G. 705 f.; Fr. 720 f. (562 f.), and Loeb, *C*. For quantitative studies see Kundt, 128 ff.; Aubert, *B*, 264 ff.; Messer; and Knox and Watanabe.

Hering, *B*, 65 ff.; Wundt, *A*, 4te Aufl., II., 142 f.; and the literature just cited.

196. Illusions in the Perception of Distances Depending on their Direction in the Field of Vision.

a. Vertical distances tend to be overestimated in comparison with horizontal distances. Lay off by eye on a sheet of paper placed vertically before the face equal distances, up, down, right and left, from a central dot, marking the distances by dots as in *A* in the accompanying diagram. Repeat several times, and measure the distances found. The illusion is said to be more marked in large figures.

In all the figures below, the vertical and horizontal dis-



tances are equal, and in all cases, except in the circle, the vertical are apt to seem too great.[1]

In *D* the overestimation of the height entails an underestimation of the angles above and below, and an overestimation of those at the right and the left. In *E* the base and the altitude are equal, though the latter seems greater. The same illusion causes equilateral triangles to seem only isosceles. Thiéry finds in the latter case (p. 116 f.) that the effect is not absolutely dependent on the vertical, but that any side taken as a base seems too short. The illusion is less in the line figures, and absent entirely in the circle, in Wundt's opinion, because in the case of these familiar figures perception is influenced by knowledge of the geometrical relations of the parts; in Thiéry's opinion, because the tendency to give them a perspective interpretation with the upper part remote is less developed (see *c* below). A similar, though slight, difference is sometimes found between horizontal distances to the right and left, when careful experiments are made with the single eye. For quantitative studies of such illusions as these, see Kundt, R. Fischer, Münsterberg, and the literature cited by them.

b. Distances in the upper part of the field are overestimated as compared with those below them. This illusion may be tested actively as follows: Near the top of a strip of paper twelve or fifteen inches long and five or six wide, draw a horizontal line about two inches long. Take this as a standard, and draw half an inch below it a second line of a length that seems equal to the first. Then cover

[1] A similar illusion attends the vision of many distant objects. Photographs with hills in the background are often disappointing, because the hills seem so much lower in the picture than in the actual landscape. An interesting test may be made by requiring a number of persons to make sketches of such landscape, and then comparing with a photograph taken on the spot. Cf. Helmholtz, *A*, G. 706 f.; Fr. 722 (564).

the first line, and taking the second as a standard, draw a third, and so on, continuing this process till the strip is full. Then uncover, and measure the first line and the last. With this Wundt associates the S's and 8's, which seem a little smaller at the top than at the bottom when in their usual position, but a good deal larger above when inverted, — S 8. For similar observations on other letters, see Thiéry, p. 97 ff.

c. The overestimation of distances in the upper part of the field seems to result from an unconscious allowance for greater distance in objects lying in that part of the field. We habitually see carpet patterns, figures in tablecloths, and similar repeated figures lying in planes parallel to the floor, as of equal size regardless of their distance. That there is a tendency to such an allowance may be shown by the following experiment: Prepare a frame a foot or more square, and stretch across it a set of six or eight parallel threads an inch apart. Hold the frame parallel to the face before a uniform background, and then tilt it slowly backward from the face till the threads begin to seem convergent above. Notice the angle of tilting, and then, returning to the vertical position, tilt the frame toward the face until the threads seem to converge below. It will generally be found that the angle is smaller in the second case, unless special effort is made to discover the convergence.

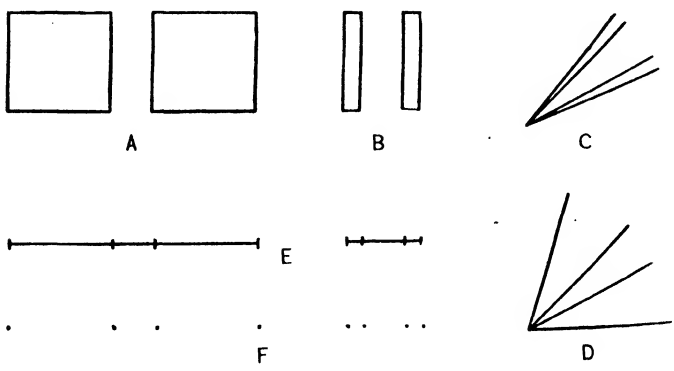
For all of the illusions of *a* and *b*, Wundt finds an explanation in the differences of effort required for turning the eye in different directions. The superior and inferior straight muscles are weaker than the external and internal. Thiéry's explanation also depends upon eye-movements, but in a different way. Depression of the plane of vision is accompanied by increased convergence, and this is associated with vision of near objects. The lower part of a fig-

ure is therefore likely to be interpreted as if nearer than the upper part. There is also a tendency to run the eye over such figures from below upward, which also favors the interpretation of the lower parts as nearer than the upper. Lipps regards the overestimation of the height of the square as an unconscious allowance for foreshortening, acquired through preponderating experience with squares lying in planes inclined with regard to the plane of vision; and Hering's explanation of the results of Ex. *c* is the same.

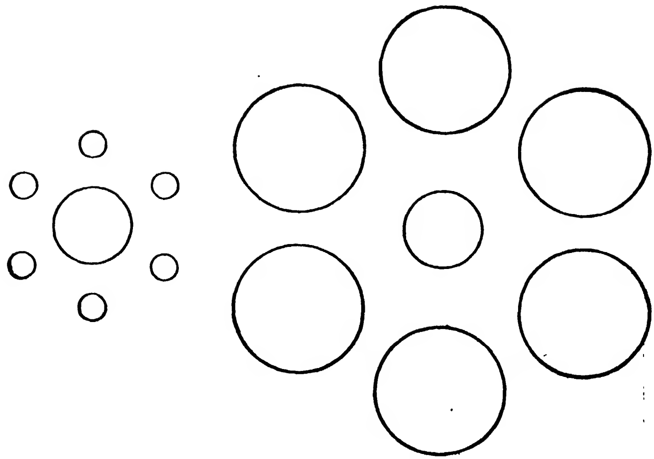
Kundt. Münsterberg, 164 f., 175 ff. Wundt, *A*, 4te Aufl., II., 137 ff. Hering, *B*, 355 f. Helmholtz, *A*, G. 684, 702; Fr. 697, 716 (543, 559). Thiéry, 93 ff. Lipps, *B*, 221.

197. Contrastive Illusions.

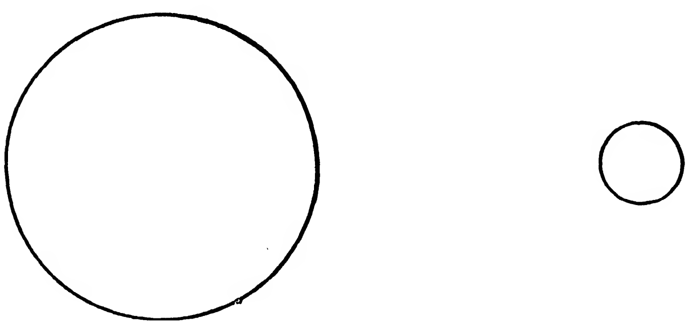
a. In figures like the first and second groups below, the middle space, angle, line, or circle seems smaller when it lies between large extents than when it lies between small extents.



The figures of the first group were introduced by Müller-Lyer, the circles by Ebbinghaus. With these probably be-

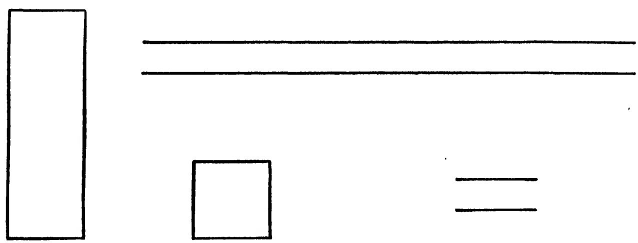


longs the following figure, devised and studied quantitatively by Baldwin. The bar is exactly half-way between the circles, but looks a little nearer the larger one.



Müller-Lyer seems to hold that the observer compares the extents in question with their surroundings as well as with each other. Thiéry cites from Classen the general statement that "the larger, longer, higher, broader the

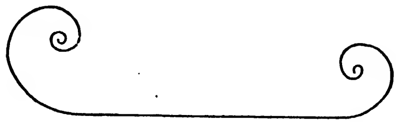
mathematical form of an object appears, the more we have reason to regard it as near; the smaller, shorter, lower, narrower, the more we imagine it at a distance;" and argues that the figures of the group of large extent are interpreted as they would be if less remote than the group of small extent, from which fact results the apparent difference in the parts of the figures which are actually equal.



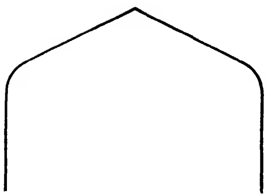
b. In a similar way, the sides and bases of parallelograms seem to contrast, the tall figure appearing narrower than the shorter; and even simple parallel lines seem nearer together or farther apart as they are longer or shorter. In this case, which is the one specially noticed by him, Wundt explains the illusion by the strong tendency to move the eyes lengthwise along the long parallels, which results in an underestimation of the figure in a vertical direction.

c. Contrast in Curvature. In the following figures from Lipps and Höfler, curved lines make adjacent straight lines seem curved in the contrary direction.

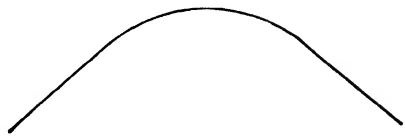
In *A* there is a slight apparent curvature of the straight line connecting the spirals. In *B* the lines for a half-inch either side of the apex are actually straight, but seem slightly convex downward. In *C* the last half-inch on either side is straight, but seems slightly curved in the same sense as in *B*.



A.



B



C

d. The illusion of Mellinghoff and Loeb.

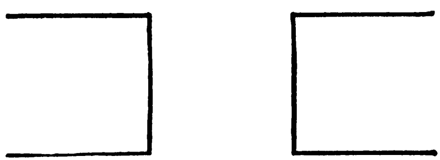
In *A* the lower line of the right pair, and the upper line of the left, are parts of the same straight line, but the addition of the parallels causes the first to seem a little too low, the second a little too high. The illusion is said to be lessened when attention is withdrawn from the added parallels. Loeb gives the experiment an active form by having strips of cardboard laid somewhat as in this diagram,

but has the head fixed, and the strips laid at one side of the median plane. He also gives quantitative results in round numbers. Heymans (*B*, 120 ff.) gives quantitative results for the median position. *B* is the figure of Mellinghoff (Wundt, *A*, 4te Aufl., II., 146). The dots are really at the level of the lower line, but seem a little too high,

especially when the figure is held so as to make the lines oblique. Loeb refers the illusion to spatial contrast; Wundt (in discussing Mellinghoff's figure) to the effect of the added parallels on the movements of the eyes in traversing the diagram. It seems possible, however, that these views need not exclude each other.

Müller-Lyer, *A*, *B*, and *C*; Thiéry, 83 ff.; Wundt, *A*, 4te Aufl., II., 146 f.; Baldwin; Aubert, *A*, 629; Lipps, *B*, 300; Höfler; Loeb, *C*.

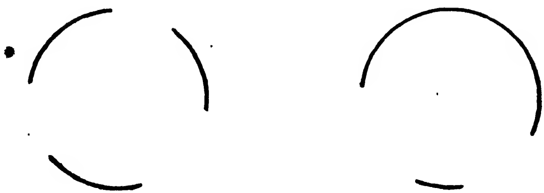
198. Contour Illusions. When one side of a quadrilateral figure is removed, the figure seems too long in the direction toward the side removed, and too short in the other direction. In the figure below, the three-sided squares seem too long in a horizontal direction, too short vertically. The reverse is the case with the space between them, which is also a square of equal size.

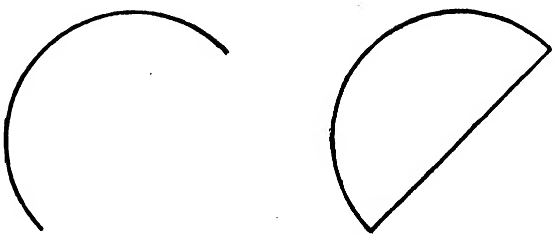


The explanation given by Müller-Lyer for this illusion is double. The open-sided squares seem too long in the direction of the open side, because a certain portion of the free space is included in the estimate (illusion of confluence); and, like the parallelogram of Ex. 197, they seem too small in the other direction because they seem too long in this.

When the circumference of a circle is interrupted, the remaining arcs seem too flat to belong to a circle of such radius; so also a semicircle seems like an arc of a greate

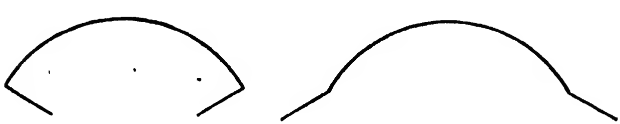
circle of less than 180° extent. Closing it by drawing the diameter makes it seem smaller.





This illusion Müller-Lyer connects with his typical figure by a transition through the next figure below, the chief difference being that the central line is now curved instead of straight.

The short, straight lines tend to shorten and bend one arc,



and lengthen and flatten the other. If short arcs of the same radius as the central ones are substituted for the short, straight lines, and then are rotated till they form a contin-

uation of the middle arcs, they will still produce the usual effect. From this would result the general principle, that every portion of an arc influences the form of every other portion, in the direction of contraction in the complete circle and large arcs, and of expansion in arcs of less than 180°. It is clear to casual observation that the diameter of a circle looks shorter than the side of a square of equal breadth.

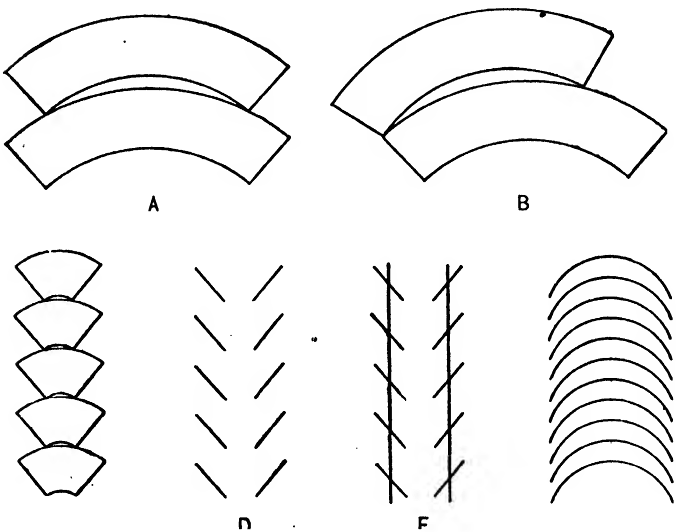
Wundt holds that the small arcs seem flat, because the movement of the eye in following them is not very remote from that for following a straight line.

Müller-Lyer, *A* and *C*; Wundt *A*, 4te Aufl., II., 149, 152; Lipps, *B*, 233 f., 290.

199. Miscellaneous Geometrical Illusions. Under this head are gathered a number of illusions, some of which can be explained more or less easily as variants of forms already considered, others that can only be brought into line with difficulty, and still others which depend on clearly different causes.

a. Ring Segments. In both *A* and *B* the upper segment seems smaller, though all are of precisely the same size. The illusion is even more striking when the segments are cut out of cardboard, and can be shifted about and actually superposed. This illusion is probably a special case of the trapezoid illusion (Ex. 192 *b*), and, like that, is related to the Zöllner figure, the transition to which is shown in *C*, *D*

and *E*. Wundt denies the explanation based on this relation to the Zöllner figure, asserting that if this were the case, the effect ought to be the reverse, i.e., the upper segment should seem larger, and gives in proof *F*, in which the upper curves seem a little larger; but he evidently has only considered the curves, and not the straight lines at the ends of the segments. His own explanation, while regarding

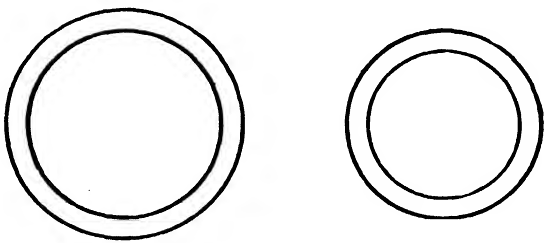


eye-movements as a primary cause, lays considerable stress on the reference of the segments to the same centre.

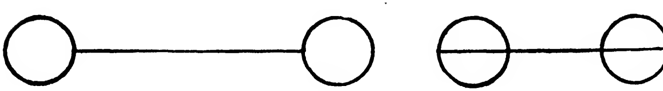
b. Concentric Circles. The inner circle in the figure at the left and the outer in the figure at the right are of exactly equal size, but the latter seems smaller.

In the opinion of Delbœuf, who introduced the figure, the illusion depends on the interference of the extra circles with the measurement of the diameter by the eye. In the

right figure the inner circle holds the eye back, as it were, and in the other the outer circle draws it on. Wundt's explanation is here, as in the case of the parallel lines of Ex. 197 *b*, the underestimation of distances in directions opposed to the chief tendency to movement. The eyes tend to follow the parallel circumferences; and this causes under-

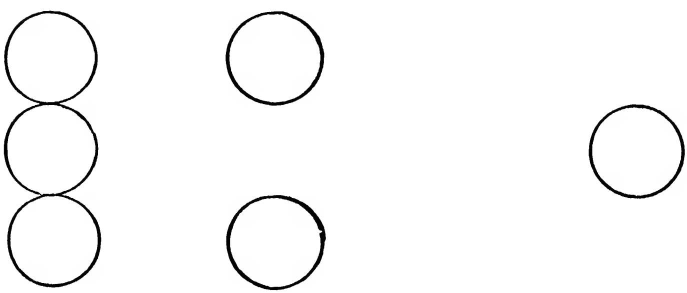


estimation of the distance between them, making the larger seem too small and the smaller too large. If this tendency to movement is opposed by a fixation mark in the centre, he finds that the illusion disappears, as in the case of the space broken by a single central dot in Ex. 195. Thiéry offers a perspective explanation, and Loeb attempts one resting on differences in accommodation.



c. Dumbbell Figures. In this figure, also from Delbœuf, the distance between the adjacent edges of the left pair of circles is the same as that between the remote edges of the right pair, though the latter looks considerably less. The illusion has been given an active form

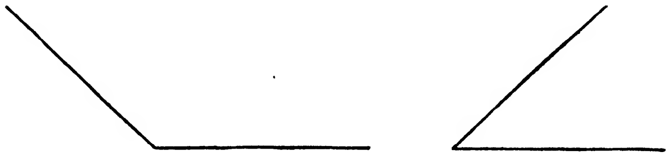
(Hopkins) by placing three like coins close together in a row, and then requiring that the middle one be moved away at right angles from the others till the distance between its edge and that of either of the others shall be equal to the distance of the remote edges of the other two. This has been done exactly in the right figure below, but to most observers the distance will seem too great. It will also be noticed that the free space between the adjacent circles in the right figure seems larger than the middle circle in the left figure.



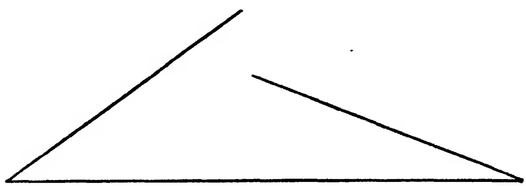
The illusion belongs to the type of Müller-Lyer's figure; and Delbœuf's explanation, as for that and for the concentric circles, is that in one figure the eye is drawn onward beyond the central line, and in the other falls short.

d. Illusions Affecting the Sides of Angles. In *A* the oblique arms of the two angles are of equal length, but that of the obtuse angle seems longer. In *B*, however, though the oblique arms are again equal, that belonging to the smaller angle seems longer. *A* originates with Müller-Lyer, who would explain the illusion on the same principle as his typical figure, parts of which these may be conceived to be. *B* was devised by Láska as a counter argument. Müller-Lyer's reply is, that the character of the figure is

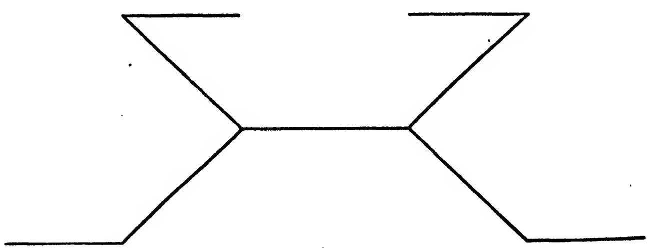
such as to give the effect of another (imaginary) line, that, namely, which would connect the free ends of the oblique lines. Such a line would form an obtuse angle with the oblique line on the right, an acute angle with that on the left, and consequently tend to lengthen the first and shorten



A



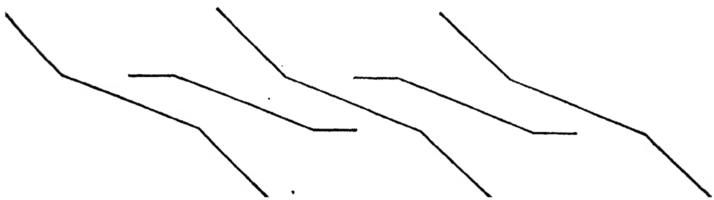
B



C

the second, which would cause the reversal of the illusion. *C* is a figure used by Lipps against Brentano's explanation of Müller-Lyer's typical figure, and is interesting in several particulars. All the lines except those that end free are

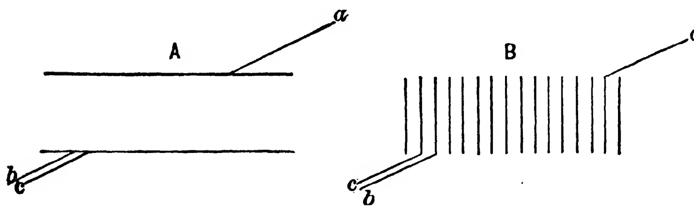
of equal length; the four that end free, though shorter than the rest, are equal among themselves; the angles between the oblique lines are right angles. All the lines adjacent to obtuse angles appear too long, those adjacent to the acute angles too short, and the central horizontal seems longer than the equal space between the inward turned ends of the upper pair of short lines.



e. In this figure, from Lipps, the five central lines are equal and parallel, but those with the short horizontal arms seem longer and more nearly horizontal than the others. Lipps uses the figure against the universality of the principle of the underestimation of obtuse angles; but to the writer, the lack of parallelism seems due rather to a tendency to judge the direction from the trend of the line groups as wholes, instead of from the particular lines to be compared. The difference in the length of the lines would seem related to the contrastive effect shown in Ex. 194 *b*, Fig. *D*.

f. In the figure at the left, though both lines are equal,

the vertical seems longer, as in the figures of Ex. 196. In the figure at the right, however, the vertical seems shorter, apparently, because of the single division of its length, as in Fig. *E* of Ex. 195.



g. Effect of Prominent Lines. The figure at the left is simply Poggendorff's figure in the horizontal position, and the illusion is of the usual character. In the figure at the right, however, this illusory effect has not only been neutralized, but actually reversed, by the change from the single pair of horizontal parallels to the more numerous vertical parallels.[1]

This change Wundt is inclined to connect with the broadening of the figure by the division of the space (cf. Ex. 195); but Jastrow and Thiéry with greater plausibility refer it to the fact that the angles in the right figure are obtuse. The horizontals are indicated, indeed, by the ends of the verticals, but are inferior in effect to the verticals actually present.

h. The Divided Triangle. The horizontal division line of the triangle, though placed at exactly half the height of the figure, seems too high, an illusion which, as Thiéry points out, the type-founders have regarded in the capital A. The illusion holds with possibly greater effect when the horizontals are replaced by concentric arcs. For quantitative results on the division of the triangle, see Thiéry, 94 f.

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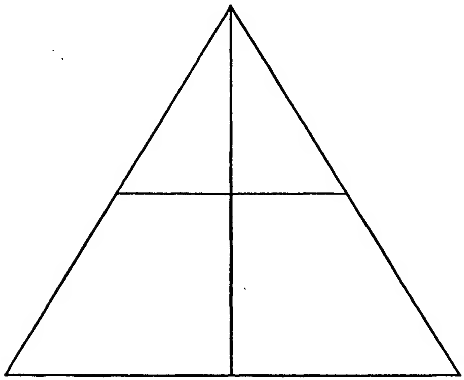
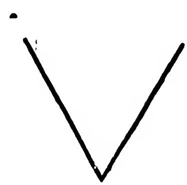
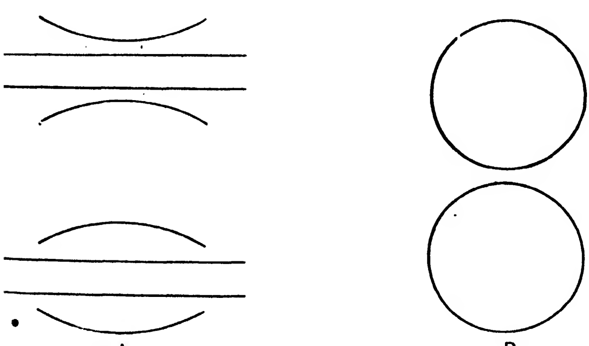
[1] These figures are taken, by permission, from Ladd's "Elements of Physiological Psychology" (Copyright, 1887, by Charles Scribner's Sons).



i. Láska's Figure. The sides of the angle in this figure are equal, but are made to seem unequal by the setting of dots at unequal distances from them. Láska offers no explanation for this illusion. Thiéry and Müller-Lyer regard it as a special case of the contrastive illusions (Ex. 197, above).



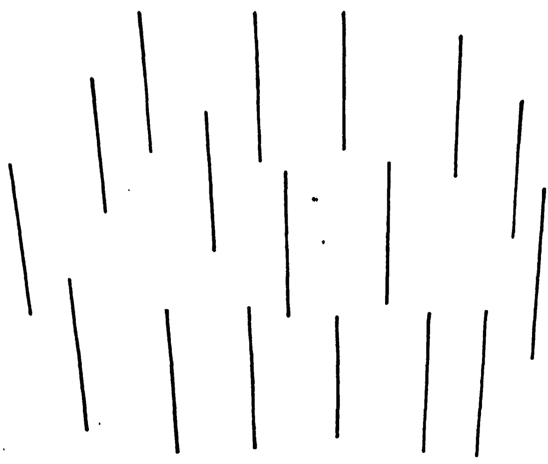
j. Adjacent Figures. In *A* the adjacent curves cause a slight illusory curvature of opposite



A

B

direction in the parallels between them. This figure might therefore be regarded as an example of the contrastive group. In *B* the circles flatten each other. The inscribed ellipse distorts the square in the direction of its long axis, but the circle in the direction of the short axis.



k. There is a certain tendency to see lines lying nearly in the visual plane, and directed toward the eye, as short vertical lines lying in planes nearly perpendicular to the visual plane. In the diagram above, the lines are all directed to a point eight or ten inches below the bottom of the diagram. When the eye is brought to that point, the

lines can be seen with a little effort as short lines nearly perpendicular to the surface of the page.

l. In the parallel columns below is shown another well-known illusion: —

In these two columns the type is of exactly the same size. On this side, however, it is set "solid," and looks smaller than on the other. According to Wundt, this is because the eye passes over the same number of letters in a shorter course.

Here the lines are "leaded;" i.e., have greater space between them. Is it not possible that the effect is based on the greater general whiteness in this case and blackness in the other?

On *a*, Müller-Lyer, *A*; Wundt, *A*, 4te Aufl., II., 151 f.; Thiéry 603 f. On *b*, Delbœuf, *B* and *C*; Wundt, *A*, 4te Aufl., II., 146 f.; Thiéry, 108 f. On *c*, Delbœuf, *C*; Thiéry, 110 ff. On *d*, Müller-Lyer, *A* and *B*; Láska; Lipps, *A*. On *e*, Lipps, *A*. On *f*, Bradley's Pseudoptics. On *g*, Wundt, *A*, 4te Aufl., II., 149; Jastrow, *A*; Thiéry, 369 f. On *h*, Thiéry, 94 ff.; Bowditch. On *i*, Láska; Thiéry, 84 f. On *j*, Wundt, *A*, 4te Aufl., II., 150 f.; Lipps, *B*, 253, 296, ff. On *k*, Christine Ladd Franklin. On *l*, Wundt, *A*, 4te Aufl., II., 150.

200. The Geometrical Illusions with Unmoved Eyes. Several of the illusions considered above are weakened when eye-movements are excluded. This may be done by fixation of the eyes, somewhat better by getting the figures as after-images, and most satisfactorily of all by instantaneous illumination. Try the effect of steady fixation on the figures of Ex. 191. The after-image method may be tried on the Zöllner figure (first figure under Ex. 191), which can be made to give a strong after-image as it stands, and on any of the other figures by cutting them as narrow slits in cardboard, and then viewing them against a bright background. The method of instantaneous illumination may be tried on any of the diagrams with the dark box and photographic shutter.

The fact that many of these illusions are still present in a certain degree when movements of the eyes are excluded,

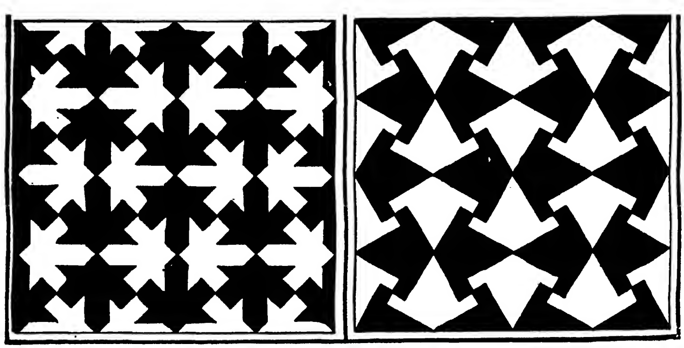
does not necessarily demonstrate that any part of them is of non-motor origin. As has already been shown in Exs. 172 and 173, the experiences of the eye in motion are retained, and applied to its perceptions when at rest.

Helmholtz, *A*, G. 709 ff.; Fr. 725 ff. (566 ff.); Wundt, *A*, 4te Aufl., II., 139; Thiéry, 328 ff.

EQUIVOCAL FIGURES.

In the Geometrical Illusions the immediate cause of the illusory perception seems to lie in some peculiarity of the figures themselves. In the Equivocal Figures, on the contrary, the varying perceptions or interpretations seem to depend more immediately on varying central or apperceptive conditions.

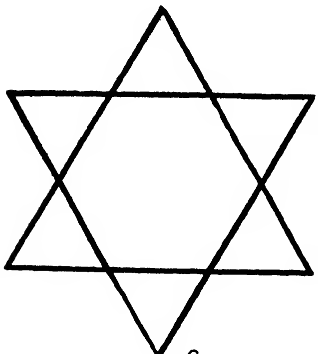
201. Plane Figures. In *A* and *B* the black and white figures are precisely alike, except in position, and either



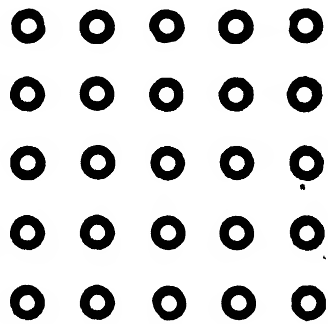
A B

may be taken as background for the other. With the change of background a change of mental attitude is involved, depending in part on this change, and in part on

the new axis of symmetry in the subordinate figures — horizontal in *A*, and vertical in *B*, if the ground is black; exactly reversed if it is white. Something similar happens in *C*, which may seem a star made up of interlacing lines,



C



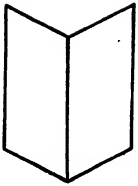
D

two superposed triangles, or a hexagon with six little triangles adjacent. In *D* the twenty-five circles of the square may be grouped among themselves in many ways: a single square of circles; five vertical or horizontal lines; two concentric squares and a central circle; an equal-armed cross filled out with four squares of four circles each, etc. A little self-observation will probably show that the change of mental attitude leads at once to a change of eye-movements, often merely incipient, by which the new patterns are followed out.

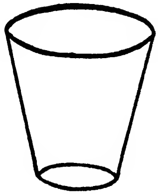
Mach, *A*, 44 ff., 87; von Bezold, 253; James, I., 442 f.

202. Diagrams with Equivocal Perspective. In the accompanying figures it is the interpretation of the space relations of the parts of the figure that changes. *E* represents a half-open book, and may be seen both concave and

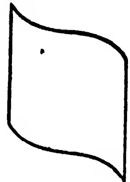
convex, the former probably being generally seen first. *F* is a glass tumbler seen from the top or from the bottom; occasionally also it may appear bent, so that both top and bottom are turned toward the observer. In *G* the curved lines are subject to interpretation as concave at the right and convex at the left, and *vice versa*. *H* is a triangular pyramid, of which the longer side is either nearest the observer or farthest from him. It also has two other interpretations; namely, as a quadrangular pyramid looked at from its apex, or a hollow quadrangular pyramid seen from below: the diagonals of the figure then appear bent towards the paper on either side of the apex. *I* is the figure known as "Necker's Cube." Notice the change in the position of the diagonal as the cube takes one position or the other. Also that the farther side is always a little too large. The inexactness of perspective from which the latter comes (both squares are of the same size) favors a double interpretation of the figure. When the perspective is correct the inversion is more difficult. (For behavior of this figure by flash illumination, see Aubert, *A*, 618.) *I* is a set of perspective cubes, which appear three in the lower row, two in the middle, and one on top; or two in the lower row, three in the middle, and two on top. This figure is evidently a reduplication of Necker's Cube. *K* represents a pair of intersecting planes, with the line of intersection nearly perpendicular to the paper, or nearly parallel to it. *L* is "Schröder's Stair Figure." It generally appears first as the upper side of a flight of steps; with some effort, however, it may be seen as the under side of such a flight, or the overhanging portion of a wall. Wundt states that if the eye follows the oblique lines of the figure in the direction *b a*, the first form is apt to be brought in; if in the direction *a b*, the second. Th figure is evidently a reduplication of *E*. *M* represent



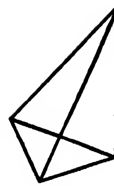
E



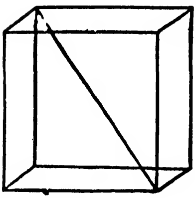
F



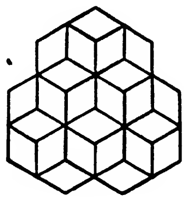
G



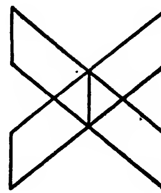
H



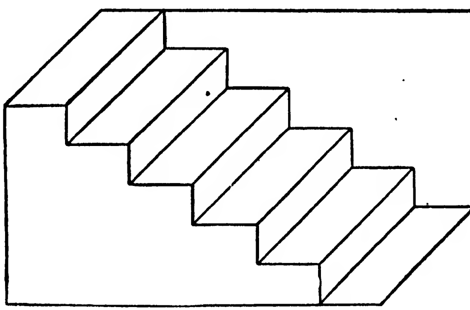
I



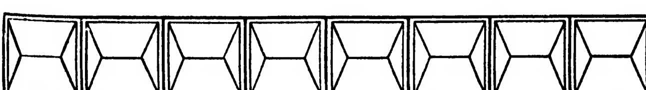
J



K



L



M

N

part of a narrow carved frieze. The little figures that compose it appear depressed or elevated. With some difficulty a part may be held as depressed while the rest are elevated; but the result is unsteady, probably because we are less accustomed to a mixture of figures in such decorations than a repetition of the same figure. *N* is similar to *M*, but introduces light and shade. Changes in the position of the figure with reference to the source of illumination generally involve a change from convexity to concavity, or *vice versa*. Cf. also the stereoscopic figures given below, many of which are capable of double interpretation when viewed monocularly.

All these perspective figures have, of course, an intermediate interpretation as plane figures, though this is sometimes hard to hold after experimenting with the tri-dimensional interpretations. Some of the changes of form are at first a little difficult for some observers, but once gotten are easier to get again. Turning the diagram upside down is sometimes helpful. Loeb reports that moving it slowly to and from the eye causes the figure to change back and forth, and Mach finds the changes brought about by slow vertical movements. The Schröder figure is caused to change by vividly conceiving the plane *a* as nearer than *b*. It is likely that these methods bring about changes in accommodation, or in the way in which the eyes follow out the figure. How far these peripheral changes would be effective by themselves, or how far apperceptive changes without peripheral expression would be effective, cannot now be said.

Notice that in all the figures changes from one interpretation to the other are invariably accompanied by other changes of greater or less extent in the position and dimensions of the lines, angles, and surfaces of the figures. In *E*, for example, when the figure is convex (the middle line

nearer the observer than the rest), all the vertical lines incline, if at all, toward the observer; when the figure is concave, they incline backward, and are longer. The relative length of the sloping lines at the top and bottom may also seem to change slightly. It is interesting to notice, with Mach, that of the infinity of possible figures which could give these diagrams as geometrical projections, only a very few extremely definite ones appear in perception.

Helmholtz, *A*, G. 770 ff.; Fr. 795 ff. (626 ff.); Wundt, *A*, 4te Aufl., II., 199 f.; Mach, *A*, 94 ff., *B*, 405 ff., *C*; James, II., 253 ff.; Lange; Loeb; Hoppe, *A* and *B*; Brewster; Sully, 95 ff.; Beaunis, II., 569; Thiéry, 318 ff., 77, 79; Wheatstone, *A*, 381 f.

203. Equivocal Figures of Three Dimensions. An inversion similar to that observed in Ex. 202 can be seen with real objects when conditions are favorable. A simple experiment may be made with a visiting-card bent in the middle so as to enclose an angle of about 120°, which gives a figure resembling *E* above. Set the card with the fold vertical on a table, where the light will fall parallel to one side, thus obviating the cross shadows in part, and look at it from a distance of a couple of yards with a single eye. The card, like *E*, may be seen either concave or convex. Notice in this case, as in Ex. 202, the change of dimension and position that takes place when the figure is changed from convex to concave. Notice, also, that when the card is seen in its illusory form (convex when it is really concave, or *vice versa*), the shadowed parts seem a deeper gray, and the illuminated parts a brighter white, than when the whole is seen correctly. The writer finds the experiment a little easier when the card is on a rather low table and he observes standing, the card then having the top of the table as a uniform background.

Very fine effects are given by casts of objects in shallow

relief, either in intaglio or cameo form. In these cases the nature of the object represented is said to be important, letters, numerals, and geometrical figures turning easily either way, but natural objects, human and animal forms, and especially faces, turning easily from concave to convex, but with difficulty, if at all, from convex to concave. Compare, for example, the ease of seeing the concave mask in Ex. 184 *a* in convex form with the difficulty of getting a convex mask to appear concave.

Most of the authors enumerated under Ex. 202 discuss these cases also.

Binocular Perception of Space.

The perception of relief, or the third dimension of objects, is considerably improved by vision with two eyes. This depends, as will be shown in experiments below, upon the difference in the aspects seen by the two eyes, and this, in turn, on the separation of the eyes. It is clear that the difference in aspect will be important for near objects, and unimportant for remote ones. For distances greater than 250 metres it is, by calculation, practically nothing, and for distances considerably less than that must be of little influence.

204. The Interocular Distance. To determine this distance, select a distant fixation point, e.g., on the horizon, fix the eyes upon it, and hold at arm's length before the face a pair of sharp-pointed dividers opened an inch and a half at the tips. These will appear slightly blurred and double, like a pair of V's side by side, — V V. Still maintaining the distant fixation, gradually spread the dividers till the inner points of the double V just touch, and the whole becomes a W. Record the separation of the points, and repeat the measurement, beginning this time with the

tips separated three inches, and gradually reducing the distance till the W is just formed. Try an equal number of times each way, and average the results. If the fixation has been carefully maintained, the separation obtained is the interocular distance. Le Conte recommends the use of slightly convex spectacles in order to obviate the blurring of the images. Verify the determination by making in a card two fine pin-holes separated by the interocular distance found. Hold this as close to the eyes as possible, bringing one of the holes before each eye. If the determination is correct, the two holes will fuse into one, when the eyes are again directed to the distant fixation point. Care should be taken, however, not to bend the card while testing, as this changes the separation of the holes. The average distance is given by Stevens as a little under 64 mm.

Le Conte, *A*, 230.

205. The Binocular Field of Vision and the Binocular Field of Regard. The portion of visual space within which binocular vision is possible at any instant is relatively small, and that within which the binocular point of regard may lie is still smaller.

a. The Binocular Field of Vision. To draw this field, arrange the head-rest of the campimeter in such a position that the lines of sight may fall perpendicularly in their primary position on the vertical plane of the instrument, and the eyes may be about 10 cms. distant from it. Fasten a sheet of paper on the plane, and mark a fixation point for each eye immediately in front of each. Close one eye, fix the other upon its mark, and, keeping the eye and head steady, dot the projected outlines of the eyebrow and nose as seen in indirect vision. It will be found convenient to bring the point of the pencil in from outside the field, and to fix points a half-inch or more apart. Repeat the pro-

cess with the conditions of the eyes reversed. A rough outline of the field required will thus be obtained.

b. The Binocular Field of Regard. When the eyes are used singly, each can be brought to fixate practically all the binocular field of vision; but the part within which lie the points that can be fixated by both eyes at the same time — the binocular field of regard — is somewhat smaller. This restriction is most marked for distant points in the lower part of the field because of the tendency of the eyes to converge as the lines of regard are depressed.

Fixate a distant spire or chimney, and, while maintaining the fixation, throw the head backward till the lines of regard are as nearly parallel to the face as possible. The fixated object will appear double, and closing one eye or the other will show the images to be such as accompany convergence of the eyes upon a point nearer than the object fixated. Cf. Ex. 208. A still easier way, suggested by Hering, is to hold a mirror close to the body, and at such an angle as to give an image of the distant object nearly vertically below the eyes. The attempt to fixate has the same result as before. It is important to steady the head to prevent its bending forward so as to give the eyes an easier position.

Hering, *A*, 442 ff.; Aubert, *A*, 609, 663 f.; Helmholtz, *A*, G. 642; Fr. 627 (484); Kirschmann, 458.

206. Indistinguishability of the Combined Fields. It is often nearly or quite impossible for an observer with normal eyes to tell which eye is affected when a change is made in one of the superposed fields. Try with two tubes of equal bore, looking through one with each eye toward the sky or other uniform background. Adjust the tubes so that the circles of light combine into a single binocular image. When they are exactly combined, have an assist-

ant thrust a pencil-point before one of them. It will be impossible without closing one eye to tell which field has been entered. If the eyes are not alike, if they differ, for example, in focal adjustment, or in degree or direction of astigmatism, means for discrimination will be present. Helmholtz finds in some cases a more or less unconscious differentiation of the fields when the needs and habits of vision favor it, and a number of the subjects tested, in a different way, by Schön were able to tell which eye was illuminated. Cf. also Ex. 218, and footnote appended to it.

Rogers, *C*; Helmholtz, *A*, G. 893 f.; Fr. 938 f. (743 f.); Schön, *B*, 83 f., *C*, 61 ff.

207. Binocular Direction. Each eye receives its impressions for itself and from its own station; but in ordinary vision, at least for points near the point of regard, the impressions of both eyes are united, and objects are perceived as if seen by a single eye midway between the other two — the *Cyclopean Eye* of Hering. It is from this median eye that binocular direction is taken.[1] A line drawn from the centre of clearest vision in this imaginary eye to the point fixated is the *Binocular Line of Regard*.

Make a pin-hole in the middle of a large sheet of paper. Hold the paper as close as possible to the eyes, and, beginning with the pin-hole at the extreme right of the visual field, move the paper slowly across the face. The pin-hole will seem to come up to the median plane, and to pass away at the extreme left, to be succeeded after an instant by a second pin-hole that repeats the same course. The impressions of the eyes singly are referred one after

[1] Schön gives experiments to show that objects at the right and left of the point of regard take their direction from the eye on their own side of the head. In the light of the experiments of Loeb (*B*), however, the matter seems to me still uncertain. Cf. Ex. 180.

the other to the cyclopean eye. For other simple experiments on this point see Helmholtz, Hering, and Wundt at the places cited below.

Rogers, *A*, 325 ff., *C*; Helmholtz, *A*, G. 756 f., 894 f.; Fr. 777 f., 939 f. (611 f., 744 f.); Hering, *A*, 386 ff., 540, *B*, 28 ff., 39 ff.; Wundt, *A*, 4te Aufl., II., 175; Le Conte, *A*, 223 ff.

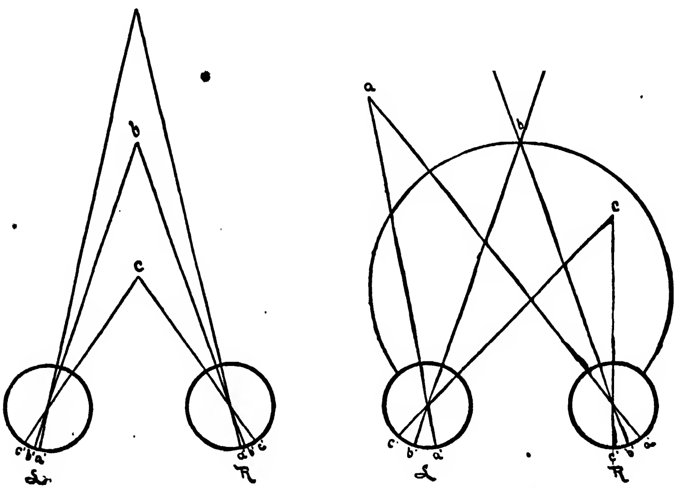
208. Single and Double Images. *a*. Hold up two fingers, one about a foot, the other about two feet, from the eyes. Fixate the nearer finger; it will be seen single, and the farther one will appear double. Fixate the farther one, and it will be seen single, while the nearer appears double. Fixate the nearer finger again, and close one eye. The image of the farther finger on the same side as the closed eye will disappear. Fixate the farther finger, and repeat the experiment. The image of the nearer finger on the side opposite to the eye closed now disappears.

The double images in the first case are called *Homonymous*, or *Uncrossed Images*; in the second, *Heteronymous*, or *Crossed Images*. The homonymous images in this case belong to the nasal halves of the retinas, and the heteronymous to the temporal halves, as can easily be seen from diagram *A*, in which L and R represent the left and right eyes respectively, *b* represents the fixation point, *a* a point more remote, and *c* a nearer point. The accented letters show the place on the retinas on which the images of the corresponding unaccented letters lie.

This particular retinal distribution is not a necessary characteristic, however; for images may be homonymous or heteronymous, and yet belong to the nasal half of one eye and the temporal half of the other, as shown for the points *a* and *c* in diagram *B* (after Hering). Roughly speaking, any point inside a circle passed through the point of regard and the optical centres of the two eyes will be

seen in heteronymous images, and any point outside in homonymous images. The nature of this circle is considered more fully in Ex. 210 and in Appendix II.

b. Double images, when both lie at one side of the point of regard, are not equally well perceived. That belonging to the eye on the same side being more distinct, and often taken as real, while the other seems illusory.



B

Fix the eyes on a distant object, and hold vertically a little to the right of the right line of regard, and about six inches from the eye, a strip of paper a centimeter wide and six or eight long, arranging it so that both images shall be projected against a uniform background. The image nearest the point of regard will be seen without difficulty; the other will be hardly discernible, and will often disappear entirely in rivalry with the part of the background seen by the corresponding part of the right eye. In this case the

images are heteronymous, and the strong image belongs to the nasal half of the right eye.

Repeat the experiment, this time fixating a pencil-point held about six inches from the eyes, and bring the paper slip up 15–20° to the right, and six or eight inches farther away than the pencil. In this case it is the image nearer the point of regard that is faint or succumbs. The stronger image belongs, as before, to the nasal half of the right eye.

Repeat either of the experiments just made, and observe which of the images it is that seems to be real and held in the fingers. A slightly increased pressure of the fingers will probably increase the definiteness of the sensation in question.

In general it is the nasal images that dominate; and this, too, it is said, whether the images are separate as in these experiments, or combined to a single image indirectly seen. See Ex. 218, footnote. For other conditions influencing the perception of double images, see Ex. 220.

* Helmholtz, *A*, G. 841 ff.; Fr. 877 ff. (695 ff.); Wundt, *A*, 4te Aufl., II., 178; Hering, *A*, 397, 424 f.; Le Conte, *A*, 92 ff.; Schön, *A*, *B*, and *C*.

209. Corresponding Points. The phenomena of single and double vision raise the question of the relative location of the retinal points in function in the two cases. The somewhat full terminology of Wundt will assist in making these matters clear. He distinguishes five sorts of points (4te Aufl., II., 173 f.): (1) *Identical Points* are points that would exactly coincide if the retinas were superposed; they might be called geometrical or anatomical corresponding points. (2) *Corresponding Points* are points whose stimulation normally gives rise to single vision. (3) *Associate Points* (*Deckpunkte*) are those whose stimulation

in a given case gives rise to single vision. (4) *Disparate Points* are non-identical points; and (5) *Dissociate Points* (*Doppelpunkte*) are points whose stimulation in a given case gives rise to double images. The dissociate points thus stand over against the associate points in the same way as the disparate over against the identical. To make the list of terms complete, a set of *Non-Corresponding Points* might also be distinguished. Both the corresponding points and the associate points are in most cases practically coincident with the identical points, and the dissociate with the disparate.

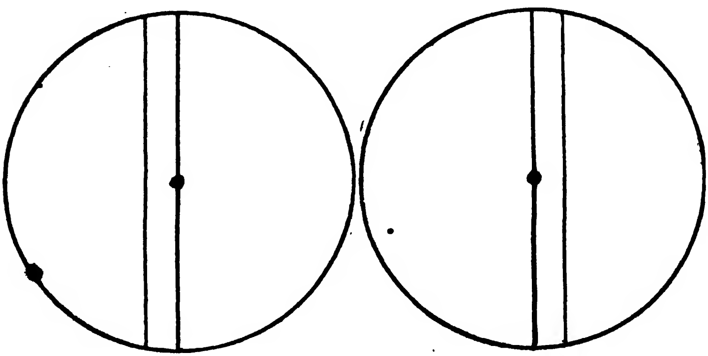
Corresponding points should not be regarded as anatomically fixed, but rather as physiological points with a certain range of co-operation. Panum's view of them as retinal "sensory circles," the central points of which when simultaneously stimulated *must* give rise to single vision, and the peripheral zones of which *may* under appropriate circumstances do the same, is in accord with the facts. Where exactness of location is important the experiment must be so arranged as to reduce the range of co-operation as much as possible. Cf. Ex. 220.

a. Corresponding Points are in general similarly situated in the two eyes. A rough demonstration may be made as follows: Prepare two exactly like figures separated from centre to centre by the interocular distance, drawing one figure in red, the other in black, to hinder fusion, e.g., a set of concentric circles overlaid by a rectangular cross. Combine these figures binocularly with the haploscope, or in any other convenient way, fixating the centres of the figures, and observe that they coincide throughout, or with only slight deviations.

For accurate methods of determining the location of corresponding points, see Helmholtz, *A*, G. 844 ff.; Fr. 880 ff., (698 ff.); Hering, *A*, 355 ff.

b. Slight Deviations from exact similarity in the arrangement of the corresponding points are found in many eyes. The most important of these is that affecting the position of the meridian of the apparent vertical, which not only varies from subject to subject, but is liable to a certain variation in the same subject within short intervals.

Arrange the haploscope for parallel vision, and fasten upon the diagram board two circles of cardboard in such a way that they may be rotated about their centres. The diameters should not exceed the interocular distance, and



their centres should be separated horizontally by exactly that distance. The lines on their surface should be arranged as in the cut above.

Adjust one of the disks so that its lines are vertical; then combine the central lines of both disks binocularly, and adjust the second disk till the outer lines in the combined image seem exactly parallel, taking pains that the plane of vision shall be approximately in its primary position. When the position of the disks is examined, it will generally be found that the lines converge slightly below. Try, also, when the lines of one disk are set horizontal and

those of the other are adjusted at right angles in the combined image.

c. The Impressions upon Corresponding Points are generally inseparable. Stare fixedly with both eyes at a small gas flame or other bright object till a strong after-image has been secured. Then holding a page of print before the face, converge the lines of regard upon a point before or behind it or with the finger-tip gently push one of the eyes out of its normal position. The images of the print will double, but the after-image will remain single. The after-images in the two eyes rest, of course, on corresponding points, and their retinal position is unaffected by the movements of the eyes, while that of all other objects is changed.[1]

On *a*, Helmholtz, *A*, G. 844 ff.; Fr. 880 ff. (698 ff.); Hering, *A*, 355 ff.; Aubert, *A*, 605 ff. On *b*, Helmholtz, *A*, G. 687 f., 850 ff.; Fr. 700 f., 889 ff. (546 f., 703 ff.); Hering, *A*, 358, 368 f.; Wundt, *A*, 4te Aufl., II., 140 ff.; Aubert, *A*, 608. On *c*, Hering, *A*, 433; Schön, *B*, 51 ff.

210. The Horopter. The last experiment but one shows that the fixation point is seen single. Besides this there are certain other parts of the visual field that may be seen single at the same time. The sum of all these parts is called the *Horopter*. The horopter varies with the fixation point, because the positions of the eyes are different. See experiments on eye-movements, p. 119 ff. An exact determination of its form in any case is extremely difficult,

[1] Whether the sensations of corresponding points are ever separable is still in doubt. Wheatstone and others have held that under proper conditions they might be separated and give rise to double vision, just as those of non-corresponding points may be united and give rise to single vision. Hering and others have held the opposite, and devised experiments to show that "Wheatstone's Experiment" is a misleading one. In support of at least a certain sort of double vision with corresponding points, see Wheatstone, *A*, 384 f.; Helmholtz, *A*, G. 885 ff.; Fr. 930 ff. (736 ff.); Wundt, *A*, 4te Aufl., II., 194 ff. Against it, see Hering, *A*, 434 ff.; Aubert, *A*, 609; Schön, *B*, 56 ff., 75 f.

but one or two rough tests of special cases may be made without much trouble.

a. Fasten two small bits of cork on the points of a pair of compasses opened two or three inches. Keep one steady, and use it as a fixation point, moving the other about it in circles in the three principal planes of the visual field (the *median plane;* the *plane of vision,* i.e., the plane passed through the lines of regard; and a *vertical plane* passed through the fixation point perpendicular to the other two). Notice the position of the moving point when double images of it can no longer be distinguished. While it will not be easy to fix these places definitely, certain regions can be made out within which the double images cannot be seen separately. One of these will be a broad band extending above and below the fixation point, and another at the right and left of that point. In these regions lies the horopter.

b. It is easy to determine with a certain accuracy the position of the part of the horopter above and below the fixation point. Hang a small weight by a black thread from a bar of the window. Select a spot behind the thread on the glass at such a height that fixation of it will bring the eye approximately into the primary plane. Fixate the point from a distance of six or eight inches, and observe that the double images of the thread are not parallel, but form a narrow V opening upward.[1] Draw the lower end of the thread away from the window, still maintaining the fixation, until the images are parallel. A straight line through the fixation point parallel to these images is the portion of the horopter sought.

c. A somewhat more definite notion of the part of the

[1] The threads may also appear slightly curved, with the concavity toward the fixation point for reasons noticed in Ex. 172.

horopter at the right and left of the fixation point can be gotten by the following experiment. Hold the frame of parallel threads prepared for Ex. 196 *c* perpendicular to the plane of vision in its primary position, and six inches or less from the face; fixate the middle thread, and observe that the threads seem to lie in a cylindrical surface slightly convex toward the face. The apparent curvature is due to the fact that the retinal images of the side threads rest on points which are disparate, though near enough together to serve for single vision.

If the threads, when actually lying in a plane, appear to lie in a convex surface, it is clear that a set of threads lying in a surface equally concave; i.e., when so arranged as to give retinal images resting on exactly corresponding points, would appear to lie in a plane.[1] This fact Hering uses in support of his principle that points lying in the horopter are actually seen in the Surface of Single Vision.[2]

As the frame is again removed the threads fall back into a plane. This effect might, however, depend on the presence of the frame. To avoid this difficulty, the experiment may be made with long threads viewed through a tube so as to cut off vision of their ends. When thus viewed from a distance, the threads seem to lie in a plane

[1] The theoretical curve in which the concave surface would cut the plane of vision is a portion of a circle passing through the fixation point and the optical centres of the eyes, the "Circle of Müller."

[2] The Surface of Single Vision, Hering's *Kernfläche*, is a transverse plane, or slightly concave surface, passing through the apparent point of regard (*Kernpunkt*). In it appear all objects whose retinal images rest on exactly corresponding points, or on points that are only vertically disparate. Behind it is the region of homonymous double images, and in front of it that of heteronymous double images. Before or behind it appear also all objects whose retinal images rest upon disparate points, even when the disparateness is insufficient to cause perceptible double images. It might be defined briefly as the surface in which the empirical horopter seems to lie. For usual positions of the eyes it stands symmetrical to the median plane and perpendicular to the plane of vision, or but slightly inclined away at the top. With extreme positions of the eyes, however, its position is altered. (Hering *A*, 401, 413 ff.)

(Helmholtz), or even a concave surface (Hillebrand). For quantitative results, see Helmholtz.

For other simple methods of determining the horopter empirically, see Schön, *B*, and Christine Ladd Franklin. For a geometrical consideration of these and other cases see Appendix II.

Helmholtz, *A*, G. 801 ff., 860 ff.; Fr. 828 ff., 901 ff. (654 ff., 713 ff.); Hering, *A*, 375 ff., 401; Wundt, 4te Aufl., II., 189 ff.; Le Conte, *A*, 192 ff., *C*, 105; Hillebrand, *A*.

211. Location of Single and Double Images. The direction in which these images appear has already been considered in Ex. 207; in the fixing of their apparent distance any or all of the criteria of visual distance may co-operate.

a. Single Images at the Point of Regard. In the absence of other criteria single images are located at the distance of the apparent point of regard. Use the haploscope adjusted for crossed vision, and any simple diagram in which the two pictures are exactly alike on the two sides. The combined image looks smaller than the original figures, and hangs in the opening of the transverse screen. Increase and decrease of the distance of the diagram is accompanied by similar movements of the combined image which lies at the crossing-point of the lines of vision; i.e., at the apparent point of regard.

Remove the diagram from the haploscope, and combine the figures with free eyes and crossed lines of sight, or use the haploscope after removal of the transverse screen. Notice that all the figures are now of nearly or quite the same size, though smaller than the original pair, and lie in the same plane. The distance of the plane is somewhat uncertain, but seems greater than that of the crossing-point of the lines of regard. The knowledge of the actual distance of the diagram by monocular and other criteria is

partly preponderant over the datum from convergence. The effect of the latter is not wholly lost, however, and shows itself in the decreased size of the circles. Cf. Ex. 217 *a*.

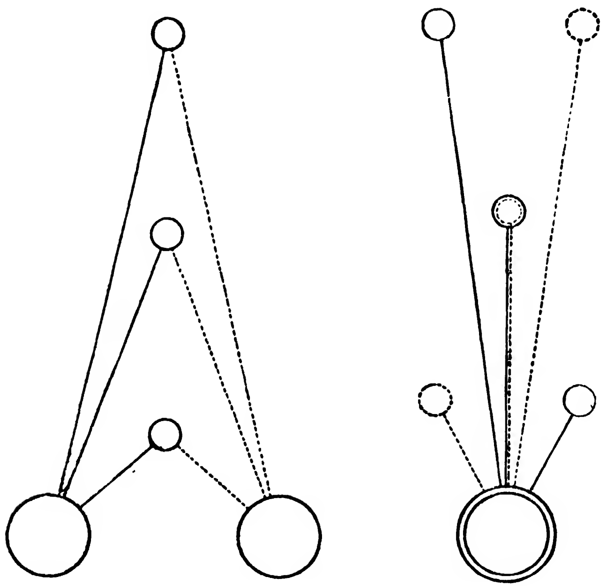
A similar experiment can also be made by combining the figures of a uniformly figured surface; e.g., a papered wall or an unpainted brick one. As successive figures are combined by greater and greater convergence, a phantom wall approaches; but location at the crossing-point of the lines of regard seems rather clearer to the writer when the convergence is being allowed to fall back stage by stage than when it is being increased. For a special study of other phenomena attending the combination of such figured surfaces, see Le Conte, *C.*

Combinations with parallel lines of sight ought on this principle to give combined images located at an infinite distance, or, more exactly, at the limit of distance for which the binocular criterion is commonly useful; but the effect is hardly to be secured with ordinary diagrams. The transparent one recommended in Ex. 212 *b* succeeds partially, when given a not too rapid motion to and from the face against a background of sky. It is not hard, however, to secure location beyond the actual plane of the figures combined. Hold up an open-meshed cane-seated chair, six or eight inches before the face, and combine the octagons of the mesh with eyes converged on a more distant point.

For location when the lines of sight are divergent, see Ex. 219 *a*. For the case of single images showing binocular relief, see Ex. 212.

b. Double Images. The single members of the double image pair are subject to location according to the usual monocular criteria, and to certain binocular criteria as well. Cf. Ex. 218 *a*. Their location as regards distance, especially when seen with unmoved eyes, is sometimes extremely

uncertain, and may even be changed voluntarily. The tendency under these conditions is to locate them at about the distance of the apparent point of regard. Try with a couple of threads or wires (not held in the hands) before a uniform background, and so arranged that the points of support cannot be seen. For careful experiments see Schön.



Their direction and approximate distance, other things being equal, may be plotted schematically according to the following rule based on the principle of binocular direction examined in Ex. 207: In order to get the position of any pair of double images, draw diagrams showing the position of the object giving rise to them with reference to the eyes singly, and then combine the two by making their

lines of regard coincide. The diagram opposite, in which the middle one of the three little circles is taken as the point of regard, will make the method clear. For fuller treatment, see Hering, *B*, and Le Conte, *A*.

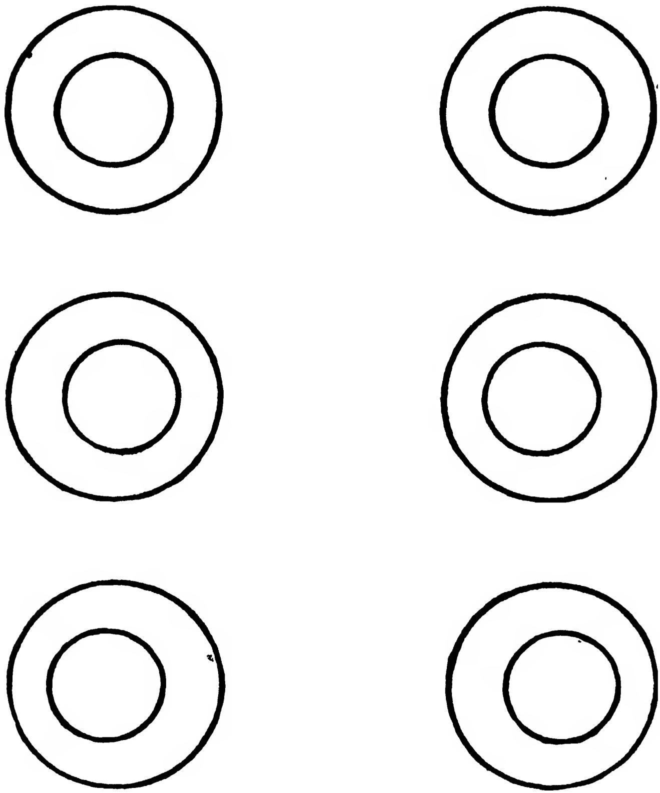
Brewster, *A*, 90 ff.; Helmholtz, *A*, G. 795 ff., 868 f., 890, 894 f.; Fr. 823 ff., 909 f., 935, 940 (649 ff., 720 f., 740, 744 f.); Hering, *A*, 426 ff., 431 f., 531 ff., *B*, 43, 167 ff.; Aubert, *A*, 613 ff.; Wundt, *A*, 4te Aufl., II., 178, 183; Le Conte, *A*, 112 ff., 213 ff.; Schön, *B*, 100 f., *C*, 50 ff.; Hyslop, *B*.

212. Binocular Perception of Relief. This rests on the perceptive union of the slightly different images received by the two eyes. Those parts of the images which lie at any instant on pairs of corresponding points are located in the Surface of Single Vision; those that lie on disparate points, though they may be seen single, are located before or behind that surface — before it, if the disparateness is such that when carried to a greater extent it would give heteronymous double images; behind it, if such as to give homonymous images: or, to state the same thing in terms of eye-movements, those parts of the object will seem nearer for the exact fixation of which an increased convergence would be required, and those parts will seem more remote for which a less convergence would be required.

a. Try with diagrams like those on the following page, combined binocularly with the stereoscope, haploscope, or with free eyes. In the first, the right and left figures are exactly alike. In the others they are different in such a way as to make the figure convex in the second diagram and concave in the third — supposing the combination to be made with lines of regard parallel, or nearly so — or concave in the second and convex in the third, if the lines of regard cross before the diagram.

The effect of identical pictures may easily be seen in the Wheatstone stereoscope by turning one of the figures up-

side-down, provided the figures are drawn in the middle of the cards. Nos. 1 and 24 of Martius-Matzdorff's diagrams show the same thing excellently in the ordinary stereoscope.



b. Combination with Free Eyes. The experimenter will find it convenient to secure the ability to combine such binocular diagrams with free eyes. The first attempts at combination with parallel lines of sight should be made

with diagrams in which the corresponding parts are at most no farther apart than the centres of the eyes; in ordinary stereoscopic pictures the distance is too great. The easiest way in which to begin is to use a diagram on glass, which may be easily prepared as follows.[1] On a suitably sized piece of glass stick two small paper dots, with their centres separated by the interocular distance. About these, but with their centres a couple of millimeters nearer together, stick two narrow paper rings; and outside these, again, two larger rings, with their centres coinciding with those of the dots.[2] The resulting diagram will be like the second one above. Hold the glass plate at arm's length, and looking through it, fixate some very distant object. The two figures will instantly combine, and the smaller ring will take its place before the other. In trying with ordinary diagrams, bring the card against the forehead, allow the eyes to take an unconstrained position, then move the diagram slowly away. Combination with parallel lines of regard is favored by holding the diagram in such a position that the eyes must turn upward to see it, the parallel position of the lines of regard being habitually associated with elevation of them. Four figures are apt to be seen at first, the middle two of which can, with care, be brought together and combined.

To combine the figures by crossing the eyes, hold the diagram at a convenient distance, and bring between it and the face, in the median plane, a pencil-point or other small object. Fixate the pencil-point, and notice the images, as in the previous case. If just the right distance has been hit, three images only will be seen; if four, move the pen-

[1] The writer is indebted for the suggestion of this experiment to the explanatory text accompanying Martius-Matzdorff's diagrams.

[2] For these dots and rings nothing is more convenient than those prepared for kindergarten use, — "Mrs. Hailmann's dots," and "gummed paper rings."

cil backward and forward till the middle two have been brought together.

One difficulty in using the free eyes comes from the habitual association of accommodation for distant vision with parallelism of the lines of regard, and accommodation for near vision with convergence; but sufficient practice will train the eyes to a more or less complete dissociation of these functions.

For literature, see any general account of binocular vision.

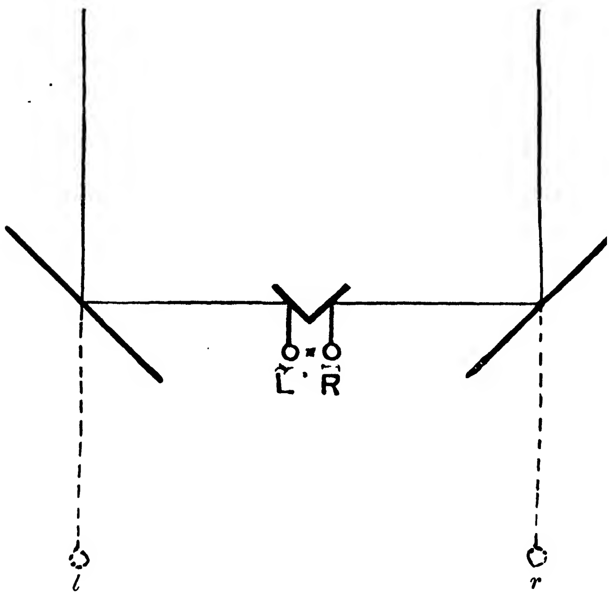
213. Increase of the Binocular Criterion; the Telestereoscope. The telestereoscope is an instrument for increasing the difference in the images of real objects received by the two eyes, and so the binocular factor in the perception of their relief. Its principle will be easily understood from the plan opposite, in which the heavy lines represent mirrors and the light lines show the course of the rays of light.

Objects reflected in the large mirrors are again reflected in the small mirrors, and so reach the eyes at *L* and *R*. The right eye thus sees objects as it would if stationed at *r*, and the left as if at *l*. For practical purposes the interocular distance has been made equal to *l r*.

Arrange the Wheatstone stereoscope for use as a telestereoscope by turning the diagram holders around and moving them out to the ends of the bed. Place it before an open window overlooking a landscape containing a good deal of detail, or even at one end of a large room — though in this case it may be advisable to reduce the separation of the mirrors somewhat. Adjust the instrument till a clear and easily combined view of the landscape is secured. The result will be a decided increase in the binocular relief of the objects seen. The effect is often that of a small model, in which, of course, for the normal eyes there would

be the same ability to see more than usual of both sides of the houses and trees, combined with the same small retinal images.[1]

Considerable trouble may be met, if the instrument is roughly made, in getting the images given by the large mirrors to stand at exactly the same height, but care in



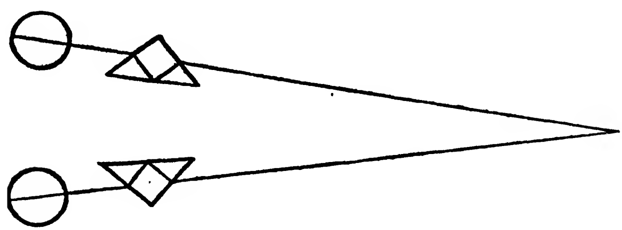
adjustment will bring them where they belong. The final position should be such as not to cause undue straining of the eyes. As in so many other binocular experiments,

[1] The difference in the binocular aspects is not the only factor, however: for mere increase of convergence, without increase of the interocular base-line, causes a very similar effect, as may be seen by examining the landscape with a 10–20° prism held before one eye (sharp edge toward the nose), while the other eye remains free.

the effect will probably become more marked as the eyes are moved about from object to object and the distances studied.

Helmholtz, *A*, G. 793 f., 831; Fr. 821 f., 861 (647 f., 681).

214. Reversal of the Binocular Criterion; the Pseudoscope. The effect of the pseudoscope upon an object seen through it is equivalent to an interchange of the images received by the eyes, so that the one seen by the right eye is like that usually seen by the left, and *vice versa*. The result, when proper conditions are observed, is a reversal or conversion of the binocular relief of the object. The instrument consists of two total-reflection prisms, set with their reflecting sides vertical, and inclining a little toward the median plane.



The right eye sees the right side of the object reflected in the right prism, and thus reversed. The left eye sees the left side of the object similarly reflected and reversed. Points in the object which normally require increased convergence now require less, and *vice versa*. In use, the instrument should be adjusted by varying the separation of the prisms and their inclination to the median plane till the images fuse easily, and with about the degree of convergence required for normal vision of the object.

The pseudoscopic effect seems quite capricious, some

objects instantly appearing in changed relief, others refusing to change. It is most certain with simple geometrical models of wire and other forms that are equally familiar in both kinds of relief (e.g., the medallions of Ex. 203), and in which the monocular criteria are weak or wanting. In other cases the reversal is difficult, or only partial. Try with simple forms of wire, and then with more complicated ones, such as boxes, bottles, or vases, and finally with the human face — a small bust, or the face of an assistant. In all cases care must be taken to avoid the interference of monocular criteria.

All the more important pseudoscopic phenomena can be gotten with stereoscopic diagrams when those intended for the right eye are seen by the left. The ordinary geometrical forms turn instantly when they are combined alternately by straight and crossed vision, either with free eyes or the haploscope. The results are partial and doubtful when more complicated figures are tried, especially if there is shading and the mathematical perspective is strong. With stereoscopic photographs failures are frequent. Try with any convenient set of stereoscopic photographs.

Wheatstone, *B*, 10 ff.; Brewster, *A*, 208 ff.; Helmholtz, *A*, G. 791 ff.; Fr. 819 ff. (646 ff.); Aubert, *A*, 625; Le Conte, *A*, 139 f.; Stevens, *A*, 447.

215. Judgments of Depth with Two Eyes. Absolute judgments of depth are difficult to experiment upon because of the difficulty of excluding relative judgments of various kinds.[1] When these are excluded the judgments are extremely uncertain, as will be shown in Ex. 217. For estimates of the distances of unknown objects under such conditions, see Wundt, *B*, and Rouse.

[1] Cf. the remarks made upon absolute judgments of the position of the lines of regard, p. 199.

Judgments of Relative Depth are easy to experiment upon, and show a surprising accuracy. In the following diagram the spacing of the letters is not strikingly different when observed in the ordinary way. When, however, the two figures are combined binocularly, considerable differences of level are to be observed.

IN	IN
THE SAME	THE SAME
PLANE?	PLANE?

The same applies to figures of any kind which show slight differences in the relative position of their parts. Indeed, the differences necessary to give relief are so slight that it is extremely difficult to draw two figures, e.g., squares or hexagons, that will lie flat when binocularly combined. Nos. 34 and 35 of Martius-Matzdorff's series are excellent for demonstrating this effect. For quantitative measurements of the accuracy of binocular judgments of relative distance, see Helmholtz, *A*, G. 790; Fr. 817 f. (644 f.); and Wundt, *A*, 4te Aufl., II., 135, and *B*.

Helmholtz, *A*, G. 788 ff., 795 ff.; Fr. 814 ff., 823 ff. (642 ff., 649 ff.); Hering, *A*, 413 ff., 551.

216. Binocular *vs.* Monocular Localization.

a. At a little distance before a uniform background stretch a thread vertically with a bit of lead. Observe the thread from a distance of 8 or 10 inches, holding a piece of cardboard of nearly that length in the median plane in such a way as to shut off from the right eye all objects to the

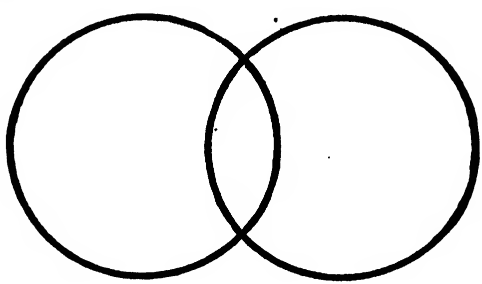
left of the thread, and from the left all objects to the right. Fixate the thread steadily for a short time, and then attempt to touch it with a pencil or teasing-needle brought up on one side perpendicular to the median plane. The pencil will of course be seen by one eye only until it is near the thread. Steadily maintaining the fixation of the thread, bring the pencil up within two or three inches, and then with a rapid movement attempt to touch the thread. The pencil will be found to pass behind it. This is the form of the experiment given by Helmholtz, who says, further, that the error is small if the head is brought into position with the eyes closed, and the touching is done immediately after opening the eyes, but that the error increases with long fixation, perhaps on account of fatigue of the eye-muscles.

In repeating the experiment, the writer has found the illusion exactly reversed by a very slight change in conditions. If the fixation of the thread is not continuously maintained, but the pencil itself is directly fixated and adjusted to the apparent distance of the thread (monocularly of course, except so far as the other eye converges consensually), the touch will fall short instead of passing beyond.

b. Differences between monocular and binocular location can also be shown with diagrams. Draw a couple of heavy circles with centres four or five inches apart. Combine them with crossed vision, and hold a pen at the intersection of the lines of regard. If the pen is now moved rapidly to and fro through the point of intersection, it will be seen now nearer and now farther than the central circle, as might be expected; but if it is moved nearer the diagram and kept there, or if it is at first brought up from that side of the point of intersection, the central circle is apt to lie in or near the plane of the diagram, or at least

beyond the pen, notwithstanding that the double images of the latter are homonymous. The nearer location of the pen probably depends on the knowledge of the distance of the hand that holds it, the greater degree of accommodation required to see it clearly (accommodation is for the true distance of the diagrams if their lines are seen sharp), and the overlapping of the circle by the images of the pen, when that occurs. These unite to give the pen its nearer and approximately correct location. It is hardly necessary to point out the small importance which such experiments allow to the convergence of the lines of regard as a visual criterion. Cf. also Ex. 217 *a.*

Somewhat similar differences of location are to be noticed when the intersecting circles of the following diagram are united binocularly. The result of union is three overlapping circles. The side circles may appear either before or behind the central one, or all may seem to lie in separate planes.



c. Several competent experimenters report that objects, especially those at a distance, look smaller when viewed with a single eye. Try the experiment, cutting off the view of one eye or the other with a bit of cardboard.[1]

[1] The writer has not had uniform success with this experiment, perhaps from the neglect of some condition not specified by those who have reported it.

d. It is by no means easy to secure either binocular or monocular vision by itself. The following experiment shows the co-operation of the second eye under circumstances which might at first seem monocular. Provide a picture showing a considerable stretch of distance, cut off the vision of one eye by holding a card an inch or so before it, fixate a point in the extreme foreground, e.g., the edge of the picture, and remove the card. The change in appearance will be slight. Cover the eye again, select a point in the extreme background, and get a clear perception of its remoteness by comparing its distance with that of objects in the foreground. Finally fixate the point selected, and remove the card. Double images of the point will be seen for an instant, showing that the eyes have assumed a degree of convergence suitable for objects more distant than the plane of the picture.

Helmholtz, *A*, G. 796; Fr. 824 (650); Hyslop, *A* and *B*; James, II., 143; Aubert, *A*, 620.

217. Changes in Convergence and in the Size of the Retinal Images.

a. Changes in Convergence, with Constant Retinal Images. This matter has already been somewhat considered in Ex. 211 *a*, but the method here described has certain advantages. Adjust the Wheatstone stereoscope so that combination of the diagrams takes place without strain upon the eyes. Then move both arms of the instrument at the same time slowly backward from the observer, continuing the combination. An increasing convergence will be required, and the apparent size of the combined

or perhaps from some difference in his eyes. When he succeeds, the decrease does not occur instantly, but a second or two after the interposition of the card. The decrease of size, when it occurs, seems to be connected with a nearer location of the object; but at times there is a reverse location, and objects seem farther away.

image will decrease, though the distance of the diagrams from the eyes, and consequently the size of their retinal images, remains constant. Moving the arms back again causes an apparent enlargement of the combined image. The same experiment may be tried roughly by cutting apart an ordinary binocular diagram, holding the parts at arm's length, combining them by crossed vision, and gradually separating the pictures while still maintaining the combination. The combined image will grow distinctly smaller as the figures are separated, and enlarge as they approach each other. Examination of the combined image in either case may show that its final situation is nearer or farther, but during the movement the change of size is the more apparent. The convergence criterion has, during the movement, little influence on the perceived distance, which is otherwise determined; but its change is effective in the apparent reduction in size. In both cases accommodation, if the images are kept clear, remains constant; and its influence, if it has any, will be in favor of constancy of apparent distance.

Retinal images of constant size can also be secured as after-images, and then the degree of convergence of the closed eyes can be altered without any direct effect of accommodation. Try with the after-image of a gas flame, gotten from a distance of eight or ten inches. Convergence will often cause both decrease of size and nearer location. Such is the writer's experience, but Scharwin and Novizki report a different result under circumstances apparently the same in all essential particulars.

b. Effects of Change in the Size of the Retinal Images without Change of Convergence. Adjust the instrument as for *a* above. Then slide both diagrams at the same time toward the mirrors or away from them. The result will be a decrease or increase of the apparent distance of the

combined image, though the degree of convergence has remained unchanged. The difference in size of the retinal image can be recognized as such; but the change of distance seems the readier interpretation, probably because of the knowledge of the simultaneous movement of the diagrams. The state of convergence seems wholly ineffective, and the result is exactly like that observed when the experiment is made with a single eye. In this case accommodation changes with change in the distance of the pictures.

The same may be tried with the haploscope arranged for parallel vision, or with the ordinary stereoscope by simply sliding the diagram holder toward the eyes or away from them.

Wheatstone, *B*, 2 ff.; Helmholtz, *A*, G. 795; Fr. 823 (649); Hillebrand, *A*, 42; Rogers, *A*, 93 ff.; Stevens, *B*, 292 ff.; Judd.

218. Movement of the Eyes in the Perception of Relief. It was supposed by some of the earlier investigators that successive fixation of the different parts of an object was necessary to the binocular perception of its relief, or, in other words, that movement of the eyes, by which the parts were successively seen single, was essential. Such movement is probably a considerable help, but is by no means necessary.

a. Hering's Experiment of the Falling Ball. Arrange a pasteboard tube wide enough to admit of binocular vision, and about a foot long, so that it shall look toward a white background a couple of yards away. A little distance from the end of the tube set up a large screen pierced by a narrow horizontal slit; e.g., 5 mm. wide and 150 mm. long. A yard or so from this hang a plumb-line, made of a silk thread and a bit of lead, in such a way that neither end of it can be seen through the slit. Let the observer look through the tube and fixate the thread. Then let the

experimenter drop a small bullet or large shot from a moderate height, a little before or behind, and a little to one side of the thread. As it passes the level of the slit, it will be seen for an instant by the observer; and he will readily be able to tell which has been done, unless the distance of the line of fall has been very nearly that of the thread. The size of the shot used should be unknown to the observer, and may well be changed from trial to trial. It should also be caught in the hand or on a thick cloth at the end of its fall, to prevent judgments based on the sound of its striking. Try, also, a few times with monocular vision for purposes of comparison and as a check. The observer should, in this case, fail about as often as he succeeds, while the distances from the thread are still such as to be almost always correctly judged with two eyes.

b. Bring the thread up within a foot of the tube, and increase the distance before or behind it at which the shot is dropped, till double images of the latter can be detected. Notice that they also are recognized as before or behind the thread. As it is somewhat difficult to see double images under these circumstances, the shot must be dropped as nearly as possible in line with the thread, so as to bring the images on either side of it.

c. Instantaneous Illumination furnishes a method of more varied application. Arrange the dark box for instantaneous illumination. Prepare several stereoscopic diagrams for special use with the box, drawing them in heavy lines on opaque cardboard, and making the distance between the symmetrical points of the paired figures not greater than the interocular distance. Through the middle points make fine needle-holes. Put one of the diagrams in place on the back wall of the box; let the observer bring the two needle-holes to combination with either crossed or uncrossed vision, and illuminate the diagram. If the

light is sufficient and the relief of the picture clear, the relation of the parts will be recognized instantly. If a single illumination is not sufficient, allow more, but at intervals of a few seconds.[1]

These experiments may be varied by instantaneous illumination of real objects instead of diagrams, or still more simply by sending single sparks through a perspectively placed Geissler tube, or by observing the irregular course of long induction sparks.

Another method of demonstrating binocular perception of relief without eye-movements has been used by Rogers and other observers. It depends on the combination of after-images successively produced in the two eyes, but is rather difficult of execution.

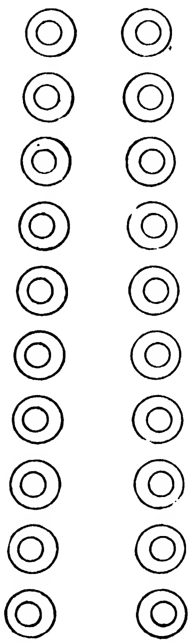
Helmholtz, *A*, G. 889 ff., Fr. 934 ff. (739 ff.); Hering, *A*, 407 f., 427; Rogers, *B*; Stevens, *B*; Le Conte, *A*, 148 ff.; Greeff; Du Bois-Reymond; Aubert, *A*, 617.

219. Unusual Eye-movements in Favor of Binocular Combination. Few of the possible movements of the eyes are under direct voluntary control, but almost any can be brought about indirectly and in a slight degree by making them temporarily necessary for single vision.

a. Divergent Movements. Slight divergent movements may be induced by bringing the arms of the Wheatstone stereoscope gradually toward the observer beyond the point giving parallel vision, while he maintains the combination of the diagrams.

[1] In order that the relief may be instantly and correctly perceived, it is obvious that the impressions received by the two eyes must never be interchanged; that, as Le Conte says, each eye should "know its own image." General comparison of the monocular fields shows little to prevent an interchange (cf. Ex. 206), but the acute observations of Schön have demonstrated that the sensations produced at corresponding points differ in definiteness, in intensity, in color, in their persistence in rivalry, and in still other respects; and on these differences probably rests the certainty of correct binocular interpretation.

The same may be secured with a diagram like that given in miniature in the margin, the observer first combining figures separated by his interocular distance, or less, and then advancing slowly, step by step, to those of greater



and greater separation. The centres of each pair of small circles are the same distance apart as the centres of the large circles in the figure immediately below; when, therefore, the smaller base of the first cone is seen single, the larger base of the second is seen single also, and so on. A certain aid may perhaps be derived from the conception of greater distance in passing from the large to the small circles, but a diagram in which the circles are concentric seems nearly or quite as helpful. Notice also that divergence makes no difference in the median forward location of the combined image, and little in its apparent distance.

b. Asymmetrical Movements. It is easy to cause one eye to turn upward while the other remains at rest, by giving a corresponding movement to one of the figures in the Wheatstone stereoscope or the haploscope; or to cause one eye to move inward and upward while the other moves inward and downward, by turning an ordinary stereoscopic diagram in its own plane, while combined with free eyes. In all cases the movement must be very gradual; and, if the combination tends to break up, a little time must be given for recombination, or a return made to an easier stage.

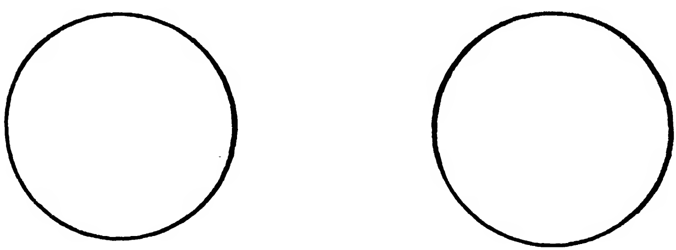
Something similar may be accomplished with a prism of

small angle first held before the eye, with the sharp edge toward the nose, and then turned slowly about the line of sight.

c. Rotation of the Eye about the Line of Sight. This may be induced by gradual rotation of one or both of the figures of a stereoscopic pair about their centres, during combination. It is well to use a fairly complicated geometrical figure; and success must be judged by the horizontals, not by the verticals, for the latter may remain single without rotation of the eye.

Helmholtz, *A*, G. 631 ff., 799 f., Fr. 615 ff., 827 f. (474 ff., 653 f.); Hering, *A*, 504 ff.; Le Conte, *A*, 252 ff.; Stevens, *A*, *B*, 290 ff.

220. Conditions that Help and Hinder the Seeing of Double Images. One of these conditions has already been



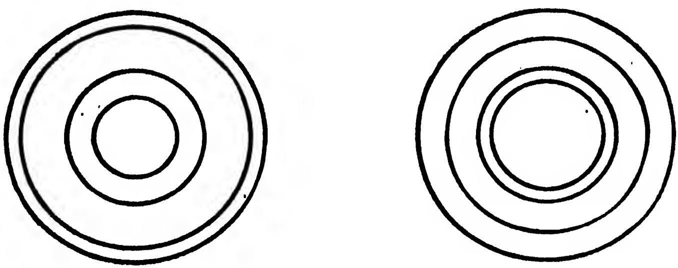
mentioned incidentally in Ex. 209 *a*; a few others are gathered here. The ability to distinguish double images seems to differ considerably from person to person; and the specifications here given may for that reason be unsuited to some observers, but the alterations required will be obvious.

a. Like Diagrams of Slightly Different Size may be combined without double images. Try with the diagram above, in which the right circle is a millimeter greater in

diameter than the left, or with Martius-Matzdorff's diagram No. 13.

The experiment may also be made by gradually moving one of the pictures away from the mirror (or toward it) in the Wheatstone stereoscope. Wheatstone points out that the union of images of unequal size is normal in vision of objects at the extreme right and left of the binocular field of regard.

b. Images Doubled Vertically are more easily distinguished than those doubled horizontally. Try with the diagram below (after Wundt). The second circle from the centre and the outer one are alike in the two figures, the first and third are unequal. The latter combine at the sides, but show double images above and below.

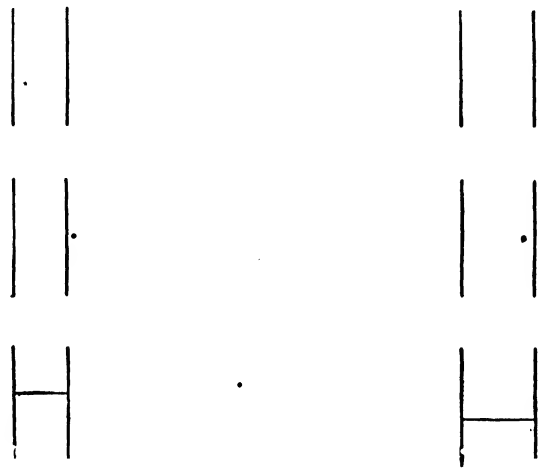


c. Slight Differences in the Figures to be combined, if not easily capable of a spatial interpretation, may hinder combination and favor double images. Try with the figures below.

Covering a portion of the right line in one of the figures of the first diagram has something of the effect of the dot in the second and the cross line in the third.

d. Movement of the Eyes, which brings one part of the images after another on corresponding retinal points, tends to obscure double images; steady fixation tends to bring

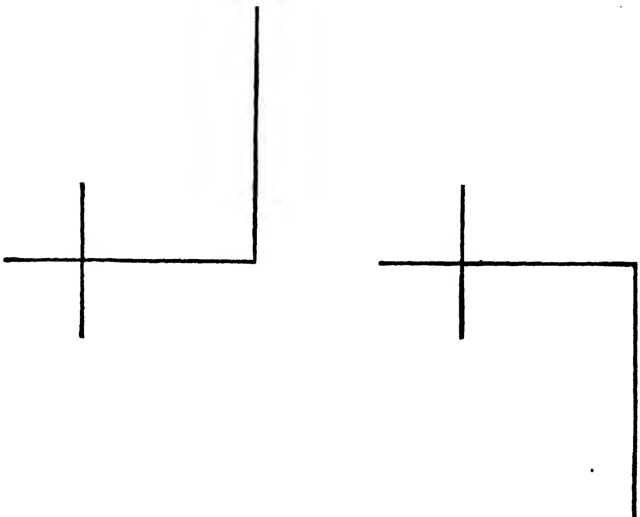
them out, especially after retinal rivalry begins. Try with the first of the diagrams below. For this reason the presence of lines in the figures which tempt the eye to movement (Wundt's fixation lines) are often a hindrance to the appearance of double images. Cf. a similar effect of eye-movements on after-images, Ex. 126.



e. If fixation is not maintained with care, double images may be neglected even near the point of regard. Combine the crosses in the diagram below, and observe that the vertical lines at the right form a more or less exactly continuous line in the combined image. Observe, further, that slight efforts toward increased or decreased convergence, which may even occur spontaneously, cause these lines to slide a little with reference to each other, while the central cross yet remains single.

Helmholtz, *A*, G. 874 ff., Fr. 916 ff. (725 ff.); Hering, *A*, 432 f.; Wheatstone, *A*, 385 f.; Rogers, *A*, (XX.) 331 ff. (XXI.) 85 ff., 181; Wundt, 4te Aufl., II., 192 ff.

221. Stereoscopy; Further Examples. The cases given below do not differ in any essential particular from those already considered in Ex. 212. They have a certain in-



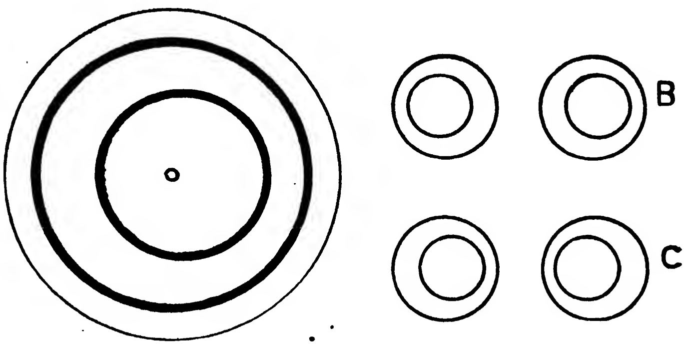
terest, however, in presenting the same principles under a variety of circumstances.

a. Stereoscopy with Moving Figures. On a disk prepared for the rotation color-mixer draw two heavy circles arranged as in *A* below, the large one exactly concentric with the disk, the small one eccentric to it.[1]

Place the disk on the spindle of the color-mixer, facing the observer, and ten or twelve feet away. Before his left eye place a total-reflection prism with its reflecting surface parallel to his median plane and its right-angle edge verti-

[1] The following dimensions will answer: Diameter of disk, 12 in.; diameter of large circle, 10 in.: diameter of small circle, 6 in.; distance of centre of small circle from centre of disk, half an inch; lines of circles about one-tenth of an inch wide.

cal — one of the prisms of the pseudoscope answers every purpose. Set the disk with the small circle at its greatest horizontal excursion on the right or left, and have the observer examine it, looking with his left eye through the prism, and with his right eye directly at the disk. If binocular combination is impossible, adjust the prism till it is secured. Then set the disk in slow rotation, and

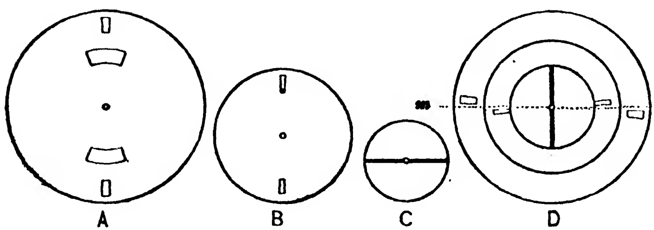


the observer will see the inner circle advance and retreat through the larger one with a sort of piston motion that is very striking. Associated with this movement are changes in the apparent size of the moving circle. The reason for the advance and retreat will be clear when it is noticed that the disk and its reflection as they turn produce in succession stereoscopic pairs in the form of *B* and *C*, with intermediate positions that serve well enough to complete the forward and backward movement.

A simpler but less striking experiment can be made as follows: Make three little plumb lines with as many bullets and silk threads, leaving the threads three or four feet long; hang these about three inches apart in one plane,

before a white background, at such a height that the bullets will be about the height of the eyes. Use the bullets as stereoscopic figures, and combine them by crossing the eyes so as to produce four images in which the middle pair consists of the image of the actual middle one combined with each of the outside ones. Now, preserving the combination, set the middle bullet swinging a very little in the plane of the threads. The result will be an apparent swinging of both middle images in planes at a considerable angle to the actual plane, and in opposite directions.

b. The Binocular Stroboscope. If a moving object is presented to the two eyes in slightly different positions, its two images, though not exactly synchronous, may be combined binocularly, and the object given a corresponding location. Try with the binocular stroboscope. Place the three disks upon the spindle of the color-mixer in the order *A*, *B*, *C*, so as to make a combination like *D* in the cut below, taking pains that the slits in *A* and *B* shall lie in radii a few degrees apart, and that the band on *C* is vertical when the line *mn* which bisects the angle between the slits is horizontal. Place the color-mixer in a good



light, and, facing it at a distance of about two feet, a mirror large enough to show the whole of disk *C*. Close to disk *A* on the side away from the mirror place a black cardboard screen pierced by a slit of length sufficient for

the use of both eyes, and not wider than the inner end of the slits in *B*. When the screen is in position the slit should lie radially to the disk at the height of its centre, and allow the observer to see the reflection of the disks in the mirror. When the disk is set in rotation he sees the band on *C* not lying in the plane of the disks, but inclined to it. Neither rate nor direction of rotation makes any difference in the apparent inclination, but change of the relative position of the slits in *A* and *B* will reduce the inclination to zero, or change its direction. The cause of the apparent inclination will be readily seen on examination of the images received by the single eyes.

The phenomenon is elegantly demonstrated with the form of apparatus used by Dvořák, but the principle involved is the same.

c. Stereoscopy by Difference in Color; Einthoven's Experiment. This depends on the chromatic aberration of the eye already noticed in Ex. 109 *b* and 184 *b*. On a background of black velvet paste at 2 cm. intervals alternate strips of blue and red paper — strips 1 cm. wide and 8–10 cm. long. Place the diagram in a good light at a distance of three or four meters, and look at it with both eyes. The different-colored strips will not appear to lie in the same plane, some observers seeing the red nearer than the blue, others seeing the blue nearer. Try also monocularly, for comparison; the difference in distance will be feeble or wanting.

The aberration depends chiefly on a slight eccentricity of the pupil, and the illusion may be increased or reversed by partial covering of the pupil. If the red has seemed nearer, a covering of the nasal halves of the pupils will bring the red still nearer, and covering the temporal halves will advance the blue. An examination of the diagrams accompanying the explanation in Ex. 184 *b* in connection

with the following simple experiment will make clear the origin of the stereoscopic effect.

On the middle of a strip of blue paper about one cm. wide by fifteen cm. long, paste a strip of red paper of the same width and five cm. long, so as to make a party-colored strip of three sections, the end ones blue, the middle one red. From this party-colored strip carefully cut a strip five mm. wide and fifteen cm. long, and mount it on a black velvet background. Place it in a good light, and view it from a distance of three or four meters with a single eye and half-covered pupil. If the right eye is used, the covering of the temporal half shifts the red portion of the strip to the right;[1] if the nasal half is covered, the red is shifted to the left. The same will be found true for the left eye, with the interchange of the terms temporal and nasal. Now, when the nasal halves of both pupils have been covered, the resultant images will be somewhat as in the accompanying diagram, where the single line stands for blue and the double line for red.

Left eye's image.

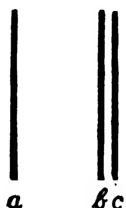
Right eye's image.

It is evident that a greater degree of convergence would be necessary for combining the images of the red part of the strip than for combining the blue.

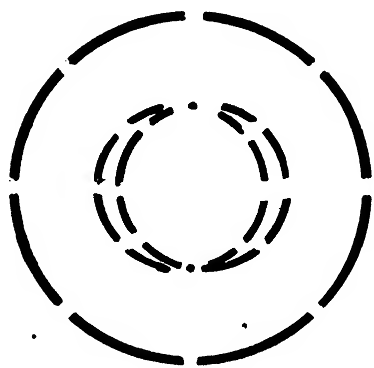
d. Anaglyphs. It is not necessary that the stereoscopic

[1] The same of course would be true if both were shifted, the red to the right, the blue to the left; but as a matter of convenience I have spoken as though the red alone were shifted.

figures should be separate, provided that they are so arranged that each eye gets its own figure only. This may be accomplished by giving a distinct color to the figure for each eye, and then looking at the combination through glasses or gelatine sheets of such color as to allow each eye to see only its own figure. Various means have been used for accomplishing this result. A simple demonstration of



A


B

it, however, may be made as follows: Cut a piece of black cardboard of such size that it will just fit into the window frame over one of the panes. In this cut three narrow vertical slits arranged like those in *A* above—making the distance between *a* and *b* about two inches, and that between *b* and *c* about a quarter of an inch. The slits themselves may be three or four inches long and an eighth of an inch wide.

On the back of the sheet, covering the slit *a*, paste a strip of white writing-paper; behind *b*, two thicknesses of red gelatine; and behind *c*, one thickness of green gelatine and one of blue.[1]

[1] **This combination works tolerably with the ordinary gelatine on hand at present in the Clark laboratory. With other kinds of gelatine other combina-**

Place the diagram in the window-frame at such a height that it will have a sky background, and look at it through gelatine combinations like those used in making it; i.e., two thicknesses of red gelatine before one eye and a thickness each of green and blue before the other. If the red is before the right eye the combined lines at the right will seem before the plane of the cardboard; if before the left eye, they will seem behind it. If the effect is not clear at first, it may possibly be helped by a little voluntary increase and decrease of convergence. The familiar truncated cone would be shown by a figure like *B* above, when properly supplied with colored gelatine behind the inner circles and paper behind the outer.

e. Stevens's Figure. Prepare for the Wheatstone stereoscope a pair of identical diagrams, each composed of three or four heavy concentric circles. Set them in the frames, and combine them stereoscopically. The result will be, of course, a flat figure. Then turn the frames slowly about a vertical axis in such a way as to make the pictures more and more nearly face the observer. The result will be a bulging forward of the central circles, giving the whole the appearance of an elliptical shield or watch-glass seen from the convex side. Turning the frames in the other direction produces a similar concave effect. The experiment can be made with equal success with a stereoscope or haploscope provided with frames that can be turned, or even with free eyes and diagrams held in the hands. Le Conte shows, however, that the effect is mixed, being due

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tions may be necessary. The thing to be sought is a combination that will stop off the red light as fully as possible. Whether the combination is the one required can easily be judged by looking through it at a bit of the red gelatine. If the latter looks black or very dark the combination will answer. Any other pairs of complementary colors would of course answer as well as the red and green used here.

in part to simple geometrical projection, and in part to binocular combination.

On *a.* Helmholtz, *A*, G. 838, Fr. 869 f. (688.); Christine Ladd Franklin, 111. On *b.* Dvořák. On *c.* Einthoven; Brücke, II., 198 f., Brewster, *A*, 126 ff. On *e.* Stevens, *B*, 297 ff.; Le Conte, *B*, 104.

VISUAL PERCEPTION OF MOVEMENT.

In the case of a slow-moving object like a planet, or even the hour-hand of a watch, the movement is clearly inferred from seeing the object successively in different places. In the case of more rapidly moving objects the movement seems to be immediately perceived. It is with the latter that this section is to deal. The first question would naturally be that of the rate at which inference gives place to immediate perception. This is by no means easy to determine, because the processes of inference and perception are extremely difficult to separate; they go on at the same time, and are alike in character. Aubert and others have put the rate, under favorable conditions, at from one to two minutes of arc per second — the eye being regarded as the centre. It is not difficult to find objects in motion at about that rate. The minute-hand of a full-sized watch (moving, say, 2 mm. per minute at the tip), when viewed at a distance of about nine inches (23 cm.), gives the slower of these rates, and other rates may be obtained in a similar way from clocks of different size.[1] The large rôle of inference in these perceptions accounts in part for the great difficulty of perceiving the motion of a single point of light in a dark field.

When the rate of movement is sufficiently rapid to make

[1] To the writer the movement of the minute-hand, even when the watch is brought closer to the face than 23 cm., seems irregular and more certainly perceptible when the hand is just passing one of the minute-marks, which would indicate that for him, at least, the rate is below that of genuinely perceived motion.

immediate perception an important factor, two methods of using the eyes can be distinguished. The eyes may be fixed upon the moving object, and move as it moves, the retinal image of the object thus remaining nearly stationary, while the images of all other objects move; or the eyes may be kept stationary, in which case the retinal image of the moving object moves, and those of other objects remain fixed. The methods do not always give the same results in perception.

222. Von Fleischl's Experiment. The rate of objects in rather rapid motion seems considerably greater when the eyes are at rest than when the eyes follow — twice as great, according to von Fleischl and Aubert. The experiment can easily be made, when riding in a street-car or carriage, by comparing the apparent rate of the ground when the eyes are fixed on one point of it after another with the apparent rate when they are fixed on the step or some part of the framework of the vehicle. In the laboratory the experiment is conveniently made with a rotating drum covered with paper carrying strongly marked lines or bands transverse to the direction of motion, before which a wire or standard is placed for fixation, or even with a simple pendulum made of a thread and a bit of lead; as in Ex. 224.[1]

Von Fleischl; Aubert, *C*; Stern.

223. Positive After-images of Motion.[2] When the eyes are suddenly closed after a brief fixation of a moving

[1] In trying with the drum and a rate of movement of about 5 cm. per second, the writer found the increase of apparent rate fairly clear when changing from eyes in motion to eyes at rest. Decrease in the apparent rate in changing in the reverse order seemed a good deal less certain.

[2] These after-images should logically have been treated with the negative after-images of motion in Ex. 128, but at the time that experiment was described

object, it is possible to observe for an instant an apparent continuance of the movement in its original direction. It seems likely that both methods of seeing motion (eyes moved and eyes at rest) furnish such images, the first through actual continuance of the movement of the eyes after the fall of the lids, and the second through a perceptive inference based upon the positive after-images present. In studying the images it is of course essential to keep these kinds separate, and to distinguish both from the "primary memory," or "memory after-image" (James, I., 643 ff.), though in normal vision all probably co-operate. The experiments seem to the writer by no means easy, and he gives them with some hesitation. The following directions, though the best that trial has yet suggested, may easily be superseded as the phenomena receive fuller study.

a. The After-images Following Observation with Moved Eyes can be secured by closing the eyes suddenly after observing vehicles passing on the street. The motion may at times seem to continue after the retinal after-image has entirely faded; and this, with the clear subjective impression of change in the direction of the eyes, seems to point to a continuation of their actual movement. The noise of the vehicle may, and probably does, contribute to this effect, and in so far the case is not a pure one. Something similar may be observed after glancing at a swinging pendulum. Here noise is not a factor.

b. The After-images Following Observation with Eyes at Rest are best secured by very brief regarding of a fairly rapid movement. The observation can be made most easily when travelling by rail, upon objects situated two or three rods from the track on the opposite side of the

the writer's attention had never been called to them. Their importance for the general theory of the visual perception of movement is sufficient justification for their consideration here.

car from that on which the observer is seated. When such objects are likely to be passed, the observer should select a point on the forward side of the window frame as a fixation point, and then close his eyes, or turn them away from the window. When his eyes are free from after-images, he should open them, or turn them again to the window, fixate the selected mark for perhaps half a second, close his eyes, and notice instantly the apparent movement of the objects seen in the after-image. In a fraction of a second this first stage of the after-image is passed and the usual sequence of colors begins (Ex. 125 *d*). In this, nothing of the moving objects can be observed, but the definiteness of the image of the window will testify to the approximate constancy of fixation. In the laboratory the moving image may be secured from a white disk a foot or so in diameter, carrying a number of heavy radial bands like the spokes of a wheel. A disk of this sort, when rotated rapidly enough to blur the outer ends of the spokes slightly, gives the effect upon closure of the eyes or the interposition of a piece of black cardboard.

This experiment seems to show that the perception of movement with the eyes at rest is based upon the perceptive interpretation of the fading train of positive after-images left by the moving retinal image, and in much the same way that the perception of relief is based on a perceptive interpretation of darkened colors in the shadowed parts of objects.[1] Otto Fischer was led to the same opinion by experiments of quite a different character; see his paper, pp. 144 f.

Stern.

[1] A certain support for this view is also to be found in the methods sometimes used in rough sketches for indicating the movement of flying cannon-balls and the like. It would be interesting to see whether a drawing of an object, followed by a shading that should fairly counterfeit the after-image train, would give the impression of movement when seen by instantaneous illumination.

224. Perception of Motion in Indirect Vision.

a. Movement may be perceived with indirect vision when the points marking its beginning and end are too near together to be distinguished with certainty when at rest. Adjust the head-rest of the campimeter eight or ten inches from the plane; fasten upon it a strip of paper a few inches wide and a couple of feet long, placing the strip horizontal with its middle in the median plane. Near the right end, and just within the field of the left eye, place four black dots, each about an eighth of an inch in diameter, at the corners of a half-inch square. Close the right eye, and find with the left a fixation point at such a distance to the left that the black dots can no longer be distinguished. In finding this point, the dots must be covered most of the time with a bit of paper like that on the plane, and the observation must be made at the instant that they are uncovered, for retinal impressions in the periphery fade with the greatest quickness. Having found the fixation point required, bring into the field radially from still farther to the right a narrow strip of the same paper, carrying at its end a dot like the four just mentioned. Observe that it is possible to perceive movements of this dot which are less in extent than the interval between the fixed dots, even when it lies farther than they from the fixation point. Measurements by Aubert and Stern showed the limen of perceptible motion to be higher in the periphery than the centre of the field, though not so much higher as might have been expected from the poor discrimination of the periphery for objects at rest. The difference between the centre and periphery of the eye in perceiving the flicker of black and white disks, mentioned in Ex. 145 *c*, is perhaps a related phenomenon.

b. The statement is sometimes made that the apparent

rate of moving objects seen indirectly is greater than that of the same objects seen directly, and certain experiments seem to give ground for the statement. It is probable, however, that this is an error, and that an important factor has been omitted in the interpretation of the experiments; namely, that in direct vision the eye follows the moving object, and in indirect it does not. When this difference is avoided, it is hard to perceive a difference in rate in the two conditions.

Hang a bit of lead by a thread a foot or less in length, so that it shall swing pendulum-wise to and from the surface of a mirror. Provide a uniform background for the pendulum, and place close to the latter something to serve as a fixation mark. Take such a position that the pendulum and its reflection shall be seen at nearly the same distance, and look at the pendulum as it swings. The reflected pendulum will seem to make somewhat greater excursions, and to move a little faster in making them. Having observed this, compare the two rates when the eye is steadily held at the fixation point. The quickening observed in Ex. 222 may appear in the pendulum itself, but little if any difference can be observed between the pendulum and its reflection.[1] If a regularly rotating drum is at hand, the experiment may be made very conveniently by covering the drum with paper lined over with heavy lines transverse to the direction of the motion of the drum, or with a strip of newspaper in which the printing is not too much broken, and observing through a couple of little windows cut in a cardboard screen placed close before the drum, one window being fixated and the

[1] In the first case, there is still another factor besides the difference of direct and indirect vision; namely, the opposite direction of the movements compared. The retinal image of the non-fixated pendulum sweeps over the retina at twice its proper rate, and underestimation of the rate of the fixated pendulum, if any, would also accrue to it.

other seen indirectly. This method has the advantage of having the movements to be compared take place in the same direction.

Exner, *B*; Aubert, *C*, 362 ff.; Dresslar; Stern, 341 ff., 362.

225. Relativity of Movement. In many cases the data for the perception of movement are equivocal; either of two interpretations is possible, and central or apperceptive conditions determine which shall prevail. Examples of this are frequently found outside the laboratory in the case of parallel railway trains, or in fording rapidly flowing streams, or when the clouds drive swiftly across the moon. Substitutes for these have been prepared (Mach, *A*, 65 f.; Budde, 131 f.; Wood); but the phenomena are perhaps sufficiently well-known without further demonstration in this connection. In the following experiment, movement may appear to be divided between the moving object and that at rest.

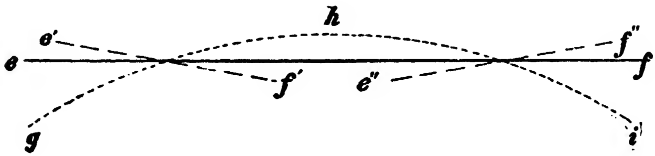
a. Move a pinhead along the imaginary line *C D* in the figure below, keeping the eye constantly fixed on the pinhead as it moves. The line *A B* will seem to move downward and to the left as the pinhead goes from *D* to *C*, and upward and to the right as it goes from *C* to *D*. Steady fixation of the pinhead is essential; and a moderate rate of movement, which can be found by a few trials, gives the best result. The right and left movement of *A B* may be increased by moving the pinhead in a line more nearly horizontal than *C D*.

An oscillating movement of the line is to be observed when a compass point is made to draw an imaginary arc

across it, cutting the line *e f*, for example, in the dotted arc *g h i*. As the point advances from *g* to *h* the line appears to take the position of *e′ f′*; as the point traverses the region about *h* there is a change, and the line inclines in the direction of *e″ f″*. As before, constant fixation of the moving point is essential.

For a somewhat similar and still more striking experiment, see Helmholtz, at the place cited below. Cf. also the apparent movements observed in the case of a pinhead moved over the Zöllner figure, Ex. 191 *b*.

Helmholtz, *A*, G. 711 ff., 763, Fr. 727 ff., 786 (568 ff., 619); Hering, *A*, 557 ff.; Wundt, *A*, 4te Aufl., II., 156 f.; Stern, 377 ff.



226. Illusory Movements of Objects at Rest. Two more or less distinguishable kinds of illusory movements of resting objects are to be observed; one in which the eyes themselves are moved in some unusual manner, and the other when their motion, if any, is slight, and fixation at least approximately constant. Examples of the first sort have been met in Exs. 50 and 177; and the general principle has been laid down, that when the line of regard is shifted voluntarily, objects normally appear at rest, but when the shifting is involuntary, objects seem to move; many further illustrations may be found in Hoppe, *C*, Chapter I. It is the second sort, however, that will be considered here.

a. Wavering of Points and Small Objects under Long Fixation. Pick out a small and isolated speck upon the wall or floor, and fixate it steadily for a considerable time,

but without straining of the eyes. After a while it will appear to move a little hither and thither, or to crawl like an insect.[1] Hoppe considers it due to slight unconscious movements of the eyes, a sort of tremor of the eye muscles. Cf. Ex. 134. Exner, however, has been led by his experiments to believe it dependent upon an uncertain and varying localization of the retinal impression, which can, in case of very small or faint stimuli, reach a considerable extent.[2] A somewhat similar movement appears when the stars are fixated continuously, and has long been known to astronomers.

b. Autokinetic Sensations. When the faint fixated point is the only thing visible in the entire field, more continuous and extended movements are to be observed — seeming sometimes as great as 20–30°. Sensations of movement of this kind have been called by Aubert "autokinetic sensations."

Arrange the dark box as for Ex. 178, but make the light point very faint by covering the pin-hole with several thicknesses of paper on the outside. Set the box so that the eyes when fixating the point shall be in an unconstrained position. Cover the head and the top of the box with an opaque cloth so as to exclude all extraneous light. Fixate the point, and observe after a time the movement in question. Notice its extent, and that it takes place while the fixation is to all appearances unbroken. Charpentier reports several observations that justify this subjective impression of fixity of fixation.

[1] Portions of the wall or floor about the speck may often seem to move with it, the movement being a sort of slow flowing, something like that in the negative after-image of motion, but not like that occurring in one direction only. Right and left movements have been chiefly noticed by the writer, but others very probably might be found.

[2] A very faint retinal stimulation may be compared in the wideness of its irradiation and the uncertainty of its location to a very faint dermal stimulation; it is, as it were, a retinal tickle. The area affected Exner calls the Circle of Action (*Aktionskreis*), and any point in this may at one time or another furnish the local coloring for the point seen.

Exner's explanation is, that in spite of the fact that fixation is continuously (and even reflexly) maintained, the false localization mentioned in *a* is operative. If this takes place successively in one direction, it brings about a continued voluntary effort at fixation, which, while it causes no actual movement of the eyes, yet gives the impression of having done so.

c. Movements of Resting Objects viewed with Eyes in Constrained Positions. Fixate the point of light as in *b*, but arrange the box so that in doing so the eyes shall be turned strongly upward or to one side. Maintain the fixation steadily, and after a few seconds the point will appear to be in motion in the direction in which the eyes are turned. The apparent motion is due to the growing fatigue (and perhaps to a partial, though unintentional, relaxation of the muscles), which is continuously met by voluntary efforts of fixation. The experiment can be made even more satisfactorily on a very small gas flame in a dark room. It shows both the tendency to take intended movements for actual ones, and the dulness of the kinaesthetic sensations of the eyes in that they do not reveal the true condition of things.[1]

Charpentier; Aubert, *C*; Exner, *A*, and the literature cited by him. On *a*, Hoppe, *C*, § 1; Exner, *A*. On *c*, Hering (Hillebrand, *B*, 150).

227. Illusions of Form depending on False Estimation of the Rate of Motion. Zöllner's Anorthoscopic Illusions.

a. In the middle of a sheet of stiff paper cut a slit a couple of inches long by an eighth of an inch wide. On

[1] This apparent movement is of the same general nature as that observed by patients suffering from paralysis of the external rectus muscle of the eye. An experiment designed to imitate their condition more exactly is given by Mach, *A*, 57 (James, II., 509); but, like Professor James, the writer has not been successful in attempting to repeat the experiment.

another piece draw a heavy black circle an inch in diameter. Place the second sheet against the back of the first, and move it rapidly from side to side in a direction transverse to that of the slit, in such a way that the circle may pass completely across behind the slit, and be seen through it. It will appear as a narrow ellipse, with its short axis lying in the direction of movement.[1]

b. Repeat the experiment just made, but this time move the circle very slowly. The result will be an apparent distortion in the contrary direction. These illusions hold equally well with figures other than the circle. In both cases the distortion appears to depend on a false estimate of the rate of motion, similar to that found for touch in Ex. 12.

Zöllner, *C*; Helmholtz, *A*, G. 498 ff., 749, Fr. 465 ff., 770 (352 ff., 605 f.); Hering, *A*, 559 ff.

228. Perceptive Inference of Motion. By this term is meant such perception of movement as takes place when no continuous movement is presented, but merely isolated phases of one. Its type is the apparent movement seen in the stroboscope, zoetrope, and similar instruments.[2] It stands midway between the cases in which movement is directly perceived and those in which it is entirely inferential; the perception depends on separate phases, but remains nearly or quite at the level of perception.

a. With the instrument at hand observe the conditions required to produce the appearance of simple movement of

[1] This illusion of Zöllner's is to be carefully distinguished from the ordinary anorthoscopic illusion of Plateau, in which the slit moves at the same time as the diagram, and in a contrary direction. In the latter the distortion can be accounted for simply as a matter of positive after-images. For information on the Plateau illusion, consult the references at the end of the experiment.

[2] The more perfect instruments of this kind, the kinetoscope, vitascope, etc., are of less psychological interest, because the phases presented are probably indistinguishable as phases, even under the most favorable circumstances.

the figures in their own stations, and of translation in the direction of the rotation of the instrument and in the reverse direction. Set the instrument in rapid movement, and observe the superposed positive after-images of several phases, noticing that the presence of several at the same time interferes with the perception of the movement.

For quantitative studies of some of the conditions of this illusion see Otto Fischer, and for notes on the history and applications of the stroboscope see both Fischer and Grützner.

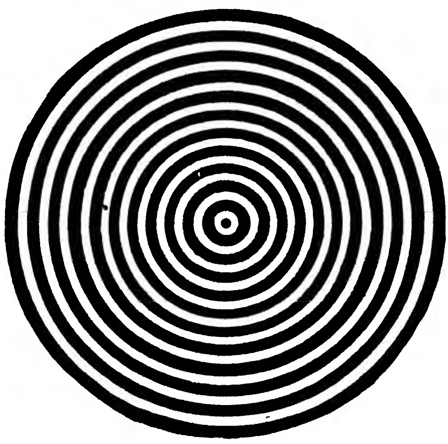
b. When important phases are wanting, the perception of the whole is often but little disturbed. This may be tried with almost any set of zoetrope pictures, but will probably succeed best with one representing a familiar movement; for example, in a strip representing a gymnast turning a somersault through a paper circle held by a second figure. The figure of the gymnast may be removed from three, or even four, successive pictures when the whole number is only thirteen, without abolishing the perception of the movement. Those covered should be such as show the figure passing through the hoop; those retained should show the beginning and end of the leap. Careful observation, however, will make clear that the gymnast disappears for an instant, and there is also a certain liability that the original conception may be supplanted by another, i.e., that the phases may be given a different interpretation; in this case, that the gymnast may seem to disappear into the hoop, and then reappear again on the same side, as he might if the covering of the hoop were elastic and he were thrown back by it.

A convenient way to remove the figure is to cut a strip of paper a couple of inches wider than the zoetrope strip, and long enough to cover three or four pictures. Lay this paper strip on the picture strip, and fold the overlapping

edges around the latter, and crease them back so that the paper will hold its place on the picture strip. Then trace the parts of the pictures to be retained, line them in, and color them to match the rest of the band. Grützner used with success the figures of boys playing leap-frog.

Helmholtz, *A*, G. 494 ff., Fr. 461 ff. (349 ff.); O. Fischer; Wundt, *A*, 4te Aufl., II., 159 f.; Grützner.

229. Thompson's Strobic Circles. The illusory motion in these well-known figures depends upon positive after-images, but in a way quite different from that noticed in Ex. 223. The important point here is the blurring to which they give rise.



a. Concentric Circles. Give to the diagram above a circular motion in its own plane, like that given to a vessel when rinsing it. The radius of the circle in which the movement is made should be quite small, and the rate 2–4 circuits per second. Observe the apparent rotation of the circles (or, more exactly, of a couple of relatively clear cut

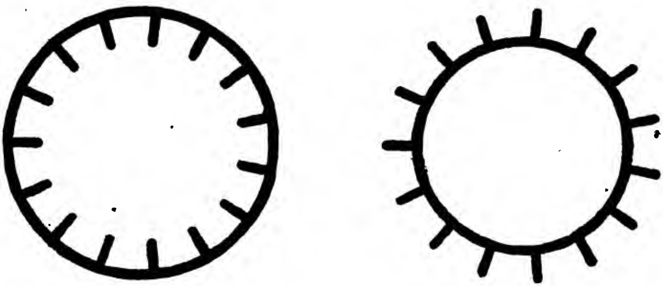
sectors), which takes place at the same rate and in the same direction as the movement given the diagram.[1]

As has been said, the illusion is a matter of positive after-images. Suppose the diagram to be given a right and left movement only, in extent equal to the breadth of one ring. It is clear that any persistence of the images will tend to blur the parts of the circles most nearly perpendicular to the line of movement (the vertical parts), while it will not affect at all those parts most nearly parallel to that line (the horizontal parts), which will consequently remain clear cut. Thus arise the above-mentioned sectors. If the movement is not quite right and left, but a little inclined toward the body at the right, it is evident that the regions most clear and most blurred will lie in a little different position from that before occupied, and in general that as the direction of the movement is changed the position of the sectors will be correspondingly changed, and, further, that as movement in a circle is movement with a continual change in direction, the positions of the sectors will also change continuously. In one complete movement of the diagram through its circuit the sectors will also have occupied once every position in the concentric circles, and the rates will therefore be the same.

Movements of the eyes may produce the same rotation with a diagram at rest. This is easiest to get when something is moved rather slowly close to or actually on the surface of the diagram, and carefully followed with the eye. The illusion is very strong in indirect vision, and movements of the eyes in observing a moving diagram in the hand will often set going others seen indirectly and actually at rest.

[1] The sectors may resemble somewhat those seen by the astigmatic eye, but are not due to that defect. Astigmatism, however, complicates the appearance, and the description which follows would apply strictly only to the perfect eye.

b. Cog Wheels. Give to the diagram below a movement similar to that used in *a*, but of not too great extent, and observe in the wheel at the left a slow retrograde movement. In that at the right, Bowditch and Hall re-



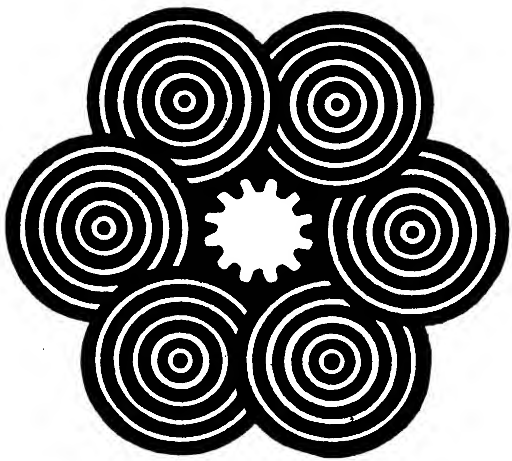
port a still slower rotation in the same direction as that of the diagram; the writer, however, has had poor success in getting this wheel to move.[1] The same effect may be observed with rack-work like that below when given the same rinsing motion, the upper rack moving to the left and the lower to the right when the rinsing movement is like that of the hands of a watch.

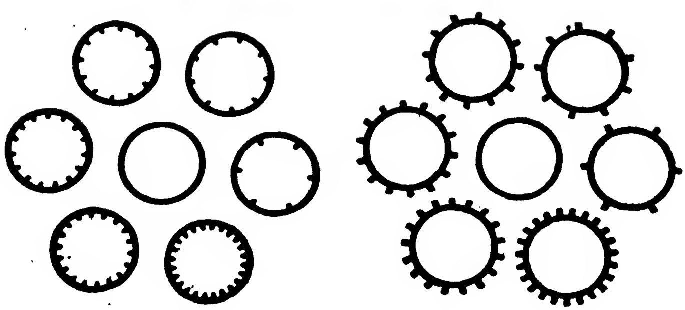
The explanation that has been offered for these figures, while perhaps deficient in some details, covers the chief phenomenon well enough. It is simplest in case of the rack-work, and rests upon two probable assumptions,

[1] These authors find a tendency to retrograde rotation in the wheel with outward cogs when the rate and extent of the movement of the diagram are considerable. This seems to be easier to get, and something of the same kind can be observed with the rayed figure of Ex. 109 *a*.

namely, that the movement is judged from the cogs rather than from the bar of the rack-work, and that the direction of the illusory movement will be suggested by that of the actual movement at such times as the cogs are most clearly seen. Suppose the diagram to be in motion in the way described, the direction being that of the hands of a watch; and suppose, further, that the upper rack at the instant under consideration is at the uppermost point of its circuit. Its movement for the instant just past has been upward and to the right, and the cogs have been rising into portions of the field occupied just before by the bar, and are therefore confused with its after-image, and not plainly seen. The cogs on the lower rack, however, have been advancing into a new part of the field, have been seen clearly, and in movement towards the right; i.e., in the direction of the rinsing. These conditions continue more or less unchanged during the instant following the point of greatest upward excursion. As the movement of the diagram progresses, however, the cogs of the upper rack begin to advance into a fresh part of the field, and those of the lower rack to retreat into the after-image of their bar; and this continues till the lowest point of the circuit is nearly reached, when the cogs of the upper rack are seen clearly, and in motion toward the left, i.e., in an opposite direction to the rinsing. In brief, when the upper rack-work is seen clearest it is moving to the left, and when the lower is seen clearest it is moving toward the right; and from these brief but clear observations the continuous movement is inferred. The racks as here represented correspond to the upper and lower parts of the wheel with inside cogs; and what was true of the racks at the upper and lower points of their circuit is true of some part of the circumference of the wheel all the time, — of that part, namely, whose cogs are at the instant most distinctly visible. If the upper and

lower racks were interchanged, so that the teeth pointed outward, they would correspond to the wheel with outside





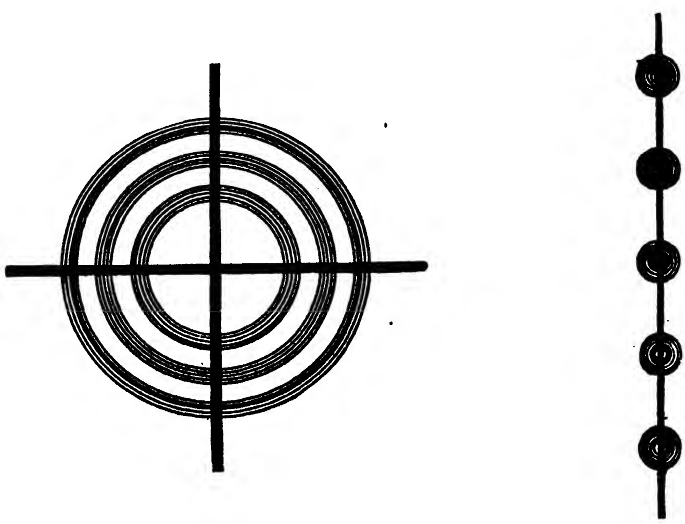
cogs; and the upper one ought, if the same principle holds, to give movement in the direction of that of the diagram, the lower in the contrary direction.

c. The first of the diagrams above (p. 317) shows a combination of the movements of both *a* and *b*. The second and third show the increasing difficulty with decreasing number of teeth in the wheels. For yet other special observations, see the paper of Bowditch and Hall.

Thompson, *B* ; Bowditch and Hall. Also the *Scientific American*, XLI., 1879, 85, 133.

230. Chromatokinopsia. Experiment of the "Fluttering Heart." This experiment, like the last, depends on positive after-images, but of a peculiar kind. The experiment takes its name from the figures with which it was at first performed, but others answer equally well.

a. Prepare a diagram like that shown in the cut below,



making the ground of red paper, the rings of blue of about equal brightness, the little circles of a variety of

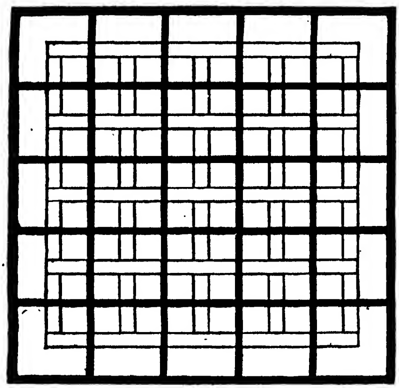
other colors, and the heavy lines in black ink. Experiment in a dark room (after allowing five or ten minutes for adaptation of the eye) or at night.

Use a small gas or candle flame for illumination, holding the diagram a yard or two from the flame, and varying the distance if the effect is not secured. Give the diagram a short side to side motion in its own plane, moving it three or four times a second, and notice an apparent slipping or springing of the rings from side to side. Close observation of the small circles of green or blue will show that it is not so much the colored figures themselves that move, as it is a whitish shimmering image that seems to rest upon them, and to hang back when the diagram is moved. Notice that the apparent movement is more marked in indirect vision. A convenient diagram for showing this is made by pasting a row of little blue circles on a strip of red cardboard. Some slipping of the remotest circles may be noticed, even when the diagram is shaken in a place no darker than a well-shadowed corner of the room. Observe, on the small circles, that all colors do not show the phenomenon equally well. The general effect is the same when the colors of the ground and the rings are reversed (blue ground, red rings); but the whitish image is no longer to be seen, and the parts of the rings at right angles to the direction of motion are darkened. With this combination of colors white cross-lines should be used instead of black. The black or white lines are relatively fixed, and thus render the apparent movement of the colors more easily discernible.[1]

b. Gray Figures on a Colored Ground and Colored Fig-

[1] An early explanation of the illusion referred it to chromatic aberration, and has recently been revived in more developed form. While it is probably a co-operating factor, it is certainly not the sole, nor even the most important,

ures on a Gray Ground show the same slipping. The gray and the color should be about equally bright. If gray rings are not at hand, prepare a diagram like that below by pasting on the colored ground gray strips about 2.5 mm. wide, and ruling heavy black lines across.[1] Observe in a dark



room as before. Try also with diagrams in which the ground is gray and the figures colored.

c. Gray Figures on a Black Ground. On a ground of black velvet fasten a small circle of black cardboard (e.g., about 4 cm. in diameter), and concentric with it a small circle of white paper (about 1 cm. in diameter). A jelly-like slipping of the cardboard will be observed when the diagram is shaken. Stronger light is required for this experiment than for most of the previous ones, a tolerable result being obtainable in a well-shadowed corner of the room by daylight. The character of the illusory movement also seems different. It is hardly necessary to say that "black" cardboard is really a very dark gray. It is

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[1] If the ground is blue, use white lines instead of black; for on the blue ground black lines themselves may seem to move.

possible under favorable circumstances to get a slipping even of a grille work of white paper on a background of black velvet.

Experiments *b* and *c* exclude chromatic aberration, and favor an explanation depending in some way on retinal inertia. The apparent slipping is due to a lag in the retinal response — to a delayed after-image, as it were, but something different evidently from the ordinary after-image. The flickering in *a* and *b* is regarded by Szili as a contrast phenomenon. The matter deserves further investigation.

Wheatstone, *C*; Helmholtz, *A*, G. 533 f., Fr. 504 (383); Mayerhausen; Szili, *A* and *B*; Schapringer.

231. Equivocal Movement Depending on Equivocal Relief. Sinsteden observed this upon windmills; but the experiment can easily be made in the laboratory by setting the disk used in Ex. 223 *b* in slow rotation, and viewing it with a single eye from a position several yards distant and nearly in its own plane. If the disk actually faces the left, and the movement is like that of the hands of a watch, a slight effort only will be necessary to make it seem to face the right with a contrary movement. For still other illusions affecting rotations, see the brief paper of Nichols, and Mach, *A*, 99 f., 102.

Helmholtz, *A*, G. 770, Fr. 795 (626).

Visual Similarity and Symmetry.

These topics lead at once to questions of æsthetics which lie beyond the scope of the present chapter. They throw light, however, upon the general question of the visual perception of figure, and are treated here for that reason. Information on their psycho-physiology is owed chiefly to Mach.

232. Visual Similarity. Figures are alike for vision,

i.e., look alike, when they present equal extents in like directions. If the first condition is not fulfilled, the figures are seen to be similar, but different in size; if the second is not fulfilled, they may be *known* to be alike, but are not immediately *seen* to be so. This will be evident from the figures below. It is only after thinking of how the central square would look from a position 45° to the right or left, or perhaps after still more complex mental operations, that we convince ourselves of the identity of the figures. In much the same way the similarity of perspective figures

is recognized, e.g., that of the sides of the cube in Ex. 188 *b*; in both instances the perceptive process is evidently not at its simplest.

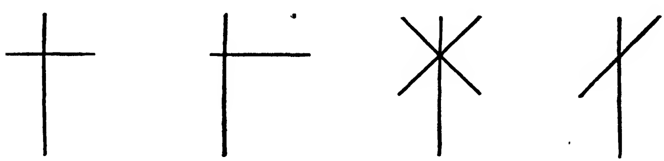
These requirements of visual similarity in the last analysis lie chiefly in the likeness of retinal images and eye-movements, perhaps also in part in the likeness of the kinæsthetic sensations of the hands in touching or tracing similar figures.

Mach, *A*, 43 ff.

233. Visual Symmetry. Symmetry is similarity of a

special kind — likeness of extent from a particular line or point. It is most common and striking when the equal extents lie on either side the median plane, as in the figures below.[1]

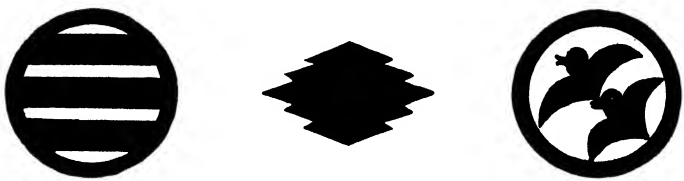
The same is to be observed almost without limit in architectural and other decorations, and even holds, as Soret shows, with simple lines. The first and third of these figures give a distinctly different impression from the second and fourth.



The extreme likeness of right and left directions is responsible for the mistakes of children with p and q and b and d, and for the elaborateness of the process through which some adults must go to tell which hand is right and which left.

[1] All the figures of this experiment, except the straight-line figures next following, are Japanese coats-of-arms taken from the *Annales du Musée Guimet, Bibliothèque d'Études*, T. III., — *Coffre à Trésor attribué au Shôgoun Iyé-Yoshi (1838-1853), Étude héraldique et historique, par de Milloué et Kawamoura,* Paris, 1896.

Pure cases of symmetry about other axes than the vertical are sometimes found, but they are less common and less simple in manner of perception. Combined vertical and horizontal symmetry is, however, by no means uncommon.



Symmetry with reference to a single point — centric symmetry — is not uncommon, especially when combined with symmetry about the vertical axis.

The letters of the alphabet, as Mach has noticed, show symmetry of several sorts in their general plan: About a vertical axis, A H I M T U V W X Y; about a horizontal axis, B C D E H I K X; about a centre, N S Z. O shows symmetry of all sorts, and F G J L P Q R are asymmetric.

The importance of eye-movements, and of the symmetry of the visual apparatus itself, is clearer perhaps in the case of symmetry than of similarity; but it must not be overlooked that not only our own persons, but nearly all the world besides, is symmetrical in plan.

Mach, *A*, 45 ff.; Soret; Pierce.

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CHAPTER VIII.

Weber's Law and the Psychophysic Methods.

The purpose of this chapter is not an extended treatment of these most technical and still debated matters, but simply the bringing together of a few demonstrations of the general nature of Weber's law, and the suggestion of a few practice experiments for the psychophysic methods, with their necessary precautions, and examples of the treatment of the results obtained. For this reason references to literature need not go beyond the text-books (Wundt and Külpe, for example), and a few easily accessible special articles. Should fuller information be desired, the student will not fail to go to original sources in Fechner, G. E. Müller, and later articles by several hands in Wundt's *Philosophische Studien.*

Weber's Law.

Weber's original discovery was that ability to distinguish stimuli depends, not on their *absolute*, but on their *relative*, difference. If, for example, the pressure of four ounces on one hand could just be distinguished from that of three ounces on the other, the pressure of four pounds would be just distinguishable from that of three pounds, and the same with other weights in the same ratio. It has also been found that when the question is not one of just observable differences, but of those much larger, the same principle of relativity holds. If, for example, a series of lights must be adjusted in such a way that the increase

of brightness from light to light shall seem equal in each case, it will be necessary to multiply the intensity each time by a constant factor, not to add to it each time a fixed amount. In general, in order to increase sensation by equal increments, it is necessary to increase the stimulus by proportional increments; or, in other words, to increase sensation in arithmetical ratio, it is necessary to increase the stimulus in geometrical ratio.

The law thus formulated is an empirical law unifying a considerable number of facts. It holds tolerably for medium stimuli of several kinds. With very large and very small stimuli it holds imperfectly, and with some stimuli it cannot be demonstrated.

The general nature of the law is shown most easily in the case of visual intensities.

234. Demonstrational Experiments for Weber's Law.

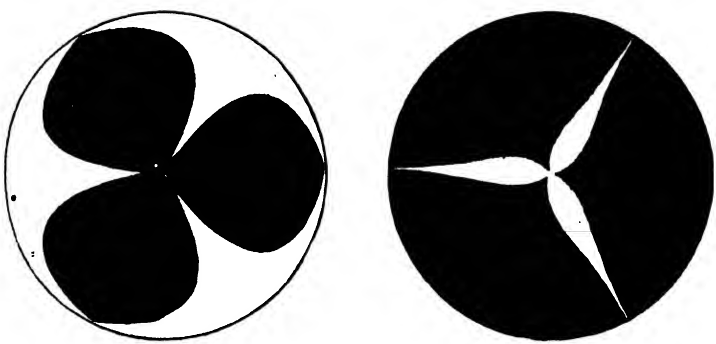
a. Transparencies. Provide a photographic transparency of a scene or object presenting a few very faint shadows or slight differences in shading. (One in the Clark laboratory shows a gray stone church with a number of slight discolorations on the roof.) The perception of these depends on the perception of the difference of intensity in the light coming through them and through adjacent parts of the transparency. To make a test of the law, therefore, it is only necessary to examine them under varied conditions of illumination. Try, for example, when the transparency is before a shaded white wall, before the same diffusely lighted, and before the same in strong light, taking care to avoid, as far as possible, reflections from the front surface of the glass. The shadows will be found about equally distinct in all cases, after the eye has become accommodated to the change. The reflection can be avoided in part by looking at the transparency through a half-inch hole in a large piece of black cardboard. A variable back-

ground can also be made by placing a large piece of white cardboard in the sunlight and changing its inclination.

Try also against a bit of clear sky near the sun. The finer shadows will be seen less well, or may entirely disappear, showing the failure of the law with stimuli of great intensity. Try also with full sunlight.

A similar test may be made by repeating Ex. 140 *b* under varying conditions of illumination.

b. Demonstration with Disks. It is not difficult to provide a gradation of intensity with rotating disks. On a disk constructed to give a geometrical increase of intensity from centre to circumference, the medium gray ought, if Weber's law holds, to stand half-way out from the centre; and such is the case. The following figures represent disks of this kind constructed by Kirschmann.

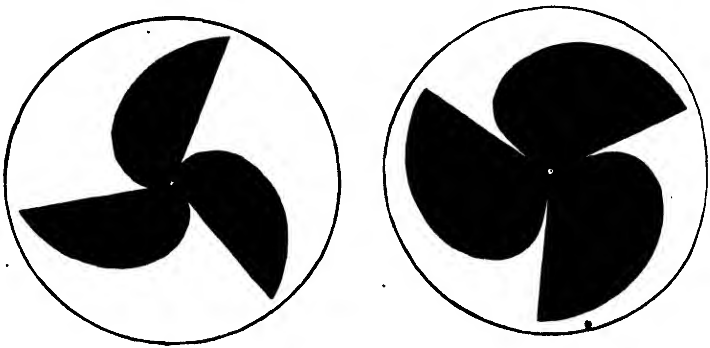


B

A gives a gradual increase in intensity from centre to circumference. *B* shows a gradual decrease. It is convenient to have also for comparison a disk in which the change is in arithmetical ratio. Such a disk is shown in *C* below. *D* gives the same geometrical gradation as *A*,

but with a different arrangement of the black on the disk; the result in both is the same.

Helmholtz, G. 384 ff., Fr. 411 ff. (309 ff.); Delbœuf, 91 ff.; Kirschmann.

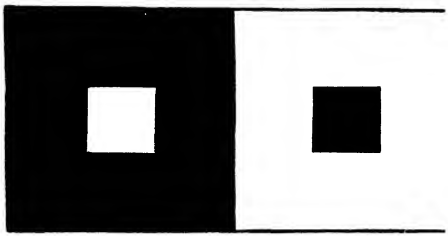


235. Irradiation. The form of this phenomenon, which consists in the enlargement of bright areas at the expense of adjacent dark ones, is known as *Positive Irradiation*, and, as usually explained, furnishes an interesting illustration of Weber's law. An enlargement of lines and points at the expense of adjacent areas, either light or dark, sometimes called *Negative Irradiation*, though wholly unrelated to Weber's law, will also be considered in this connection.

a. Positive Irradiation. Diagrams like that on the opposite page, when strongly illuminated and viewed from a little distance, show the white square slightly larger than the black, though both are actually of a size.

The enlargement is unmistakable when a diagram presenting greater differences of illumination between the light and dark parts is secured by cutting the latter from

black cardboard, mounting them on glass, and viewing the whole against the sky or a brightly lighted surface. The effect is also very marked when a ruler or straight-edged

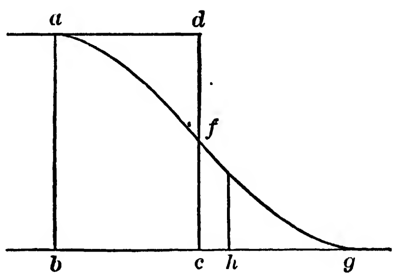


piece of cardboard is held before a flame. The flame seems to cut into the edge, — the brightest parts most. When the new moon "holds the old moon in its arms," the crescent seems to belong to a larger disk than that between its tips, and many other illustrations may be met in common experience.

The illusion, as Helmholtz explains it, depends on a slight blurring of the line of demarcation between the black and white areas — a blurring which is very marked when the illumination is strong and accommodation is inexact, and is not entirely absent even when accommodation is at its best. The contour is thus spread out into a narrow gray band, lying partly in the black and partly in the white, and shading over from one to the other. The intensities of light in different parts of this band are represented in the curve shown on the next page. The point c is taken on the actual line of demarcation; the region to the left represents the white area, that to the right the black.

If there were no blurring, the white would extend up to $c\,d$, and there cease, and the intensity curve would be $a\,d\,c\,g$.

With the blurring, we have full white to the left of *a*, and full black to the right of *g*, and the gray band of transition between, with intensities represented by the curve *afg*. This curve, however, shows intensity of light, and not intensity of sensation. According to Weber's law, the just observable change in sensation would require a more considerable change in stimulus at the intense end of the curve than anywhere else, and any less change would pass entirely unperceived. If the white were very intense, — so intense that a practical maximum of sensation were reached with an intensity *h*, — no difference could be perceived to the left of *h*, and the white would seem to extend in full intensity to that point, enlarging its area by *ch*. If the middle gray of the band, instead of the white edge, were

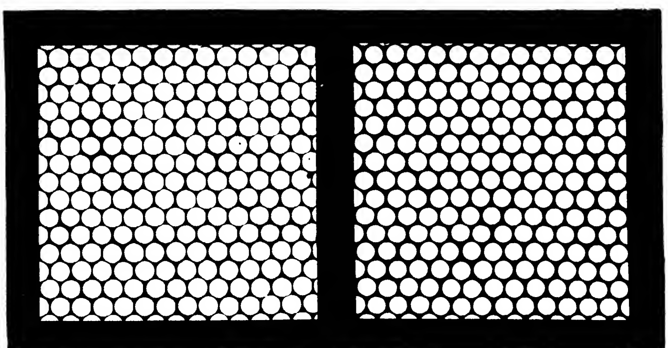


taken as the boundary, that also would be found to lie too far to the right, and would enlarge the white area. The importance of high illumination in the white, and complete blackness in the black, is evident in either case. The illusion would admit the same explanation whether the blurring were due to a physical dispersion of the light on the retina, or to a physiological spread in the nervous elements.

b. Negative Irradiation. In this case the line or point is given the benefit of practically all of its gray border, near the outer edge of which there is, according to Helm-

holtz, a relatively sudden increase of brightness (or decrease in the case of a white line on a dark ground) which fixes the apparent boundary. Because of this difference in the nature of the phenomenon, Helmholtz would prefer not to call this irradiation at all.

The combined action of positive and negative irradiation seems to account for the tendency of the white circles in the following diagram to take an hexagonal shape when viewed from distances that make accommodation inexact. The larger triangular areas suffer by positive irradiation of the circles, while the portions where the circles approach



nearest each other owe their preservation to negative irradiation.

Negative irradiation may also be demonstrated as follows. On smooth whit paper draw two fine black lines (.25 mm. or less in br adth), intersecting at an angle of one or two degrees. Hold the paper at arm's length, and determine by eye the place where the white space between the lines is equal in breadth to one of the lines. Mark

the point lightly with a pencil, and examine it under a lens. It will be found that the separation at the point selected is too great, the breadth of the lines having been overestimated.

Helmholtz, G. 394–402, Fr. 425–433 (321–327); Hering; Aubert, 575 ff., 581 ff. All of these refer to further literature.

236. Weber's Law in the Classification of Stimuli. It has been found that when a large number of slightly different stimuli are arranged in groups that seem to form a series with equal differences, the average intensities of the groups conform more or less exactly to Weber's law. This has been proved to be the fact on a magnificent scale in the grouping of the stars in magnitudes, and a rough demonstration by a similar method is not difficult to make in the laboratory.

Prepare a large number of weights, each differing slightly from the other, by enclosing pieces of sheet-lead in stout envelopes. (Cf. Chapter IX. for further details.) Select the lightest and the heaviest of the lot, and give them to the subject as standards from which he may from time to time refresh his memory of the range of the series. Then require him to arrange the rest in five classes, about equally separate in the intensity scale. When all have been classed, allow the subject to go over each group, and revise his rating if he desires. Finally, find the average weight in each group (by weighing the whole group at once and dividing by the number of envelopes in it), and calculate the ratios of these from group to group.

The following records of a trial with four subjects may be interesting for comparison. A series of 118 envelopes, ranging approximately from 5 to 100 grams, was sorted. In the table below, the groups are indicated by Roman numerals, beginning with the lightest.

SUBJECTS.	*Ratio of II : I.*	*Ratio of III : II.*	*Ratio of IV : III.*	*Ratio of V : IV.*
Sh.	1.85	1.86	1.77	1.77
St.	1.51	1.90	1.62	2.16
D.	2.39	1.68	1.58	1.52
C.	1.34	1.84	1.73	1.96

The first shows a fair approximation to the constancy of ratio required by the law. The third and fourth give some evidence of it from the second group on.

This method of demonstration is a special application of the Method of Average Error to difference comparison. The general method is considered more fully below. Classification has been tried by Jastrow with extents, both visual and kinæsthetic, and time intervals, and by Leuba on artificial stars.

Jastrow, *B* and *C*; Leuba.

THE PSYCHOPHYSIC METHODS.

In the quantitative study of sensations and stimuli, four questions arise: (1) What is the least amount of a given stimulus that will cause a sensation at all (the "initial threshold")? (2) What amount of stimulus applied to one region of the body, or under one set of circumstances, seems exactly equal to a given amount applied elsewhere, or under other circumstances (equivalent stimuli)? (3) What is the least difference that can be perceived between two given stimuli (the "differential threshold")? (4) What is the relation of several stimuli when their differences among themselves seem equal?[1]

[1] In Külpe's terms these questions are those of (1) Stimulus determination, (2) Stimulus comparison, (3) Difference determination, and (4) Difference comparison.

It is in attempting to answer such questions as these that the psychophysic methods have been developed. They are three in number: The Method of Minimal Change, the Method of Right and Wrong Cases, and the Method of Average Error. They have been most frequently applied in determinations of the least observable difference of stimuli (question 3, above), and in that connection can be readily made clear.

The most natural way of finding such a difference is to begin with the stimuli equal, and very gradually change one of them till the fact of change is just apparent. This is the Method of Minimal Change, — the method used in a number of experiments in earlier chapters, and explained somewhat fully in Ex. 24.

An indication of the amount of the just observable difference may also be found, but less directly, if the two stimuli are made a little different, and the subject is required to judge of their relative condition a large number of times. If they are quite different he will perceive the difference with a good deal of certainty, and judge right nearly every time; if they are very little different, he will be guided largely by chance, and judge wrong nearly as often as right. The proportion of right judgments in a long series of trials taken in connection with the amount of difference between the stimuli used, makes inference possible with regard to the just observable difference. This is the Method of Right and Wrong Cases.

The third method, like the last, is indirect, and gives, instead of the just observable difference, a quantity bearing a more or less constant relation to it. One of the stimuli is put under the control of the subject, and he is required to adjust it to equality with the other. His adjustments will often be slightly in error, sometimes by excess and sometimes by defect. The range of these devi-

ations will evidently bear some relation to the least difference that he can perceive; and on this fact is based the Method of Average Error.

The methods thus rudely sketched have received considerable elaboration in actual use, and certain precautions have been found necessary, the most important of which will be noticed below.

In theory, any of the methods might be used for answering all four questions. As a matter of fact, however, some are much better adapted for certain purposes than others, and all are more or less modified by the special conditions under which they are used. The Method of Minimal Change has received a variety of names in its special applications which, unless noticed, may lead to confusion. In determinations of stimuli that appear equal under different circumstances, it has been called the "Method of Equivalents." In determinations of the least observable difference of stimuli it has been called the "Method of Just Observable Difference," or the "Method of Minimal Change," in a restricted sense. In determinations of equal differences it has been called the "Method of Mean Gradation."

Though developed in the first instance for the study of Weber's law, these methods have a much wider usefulness as tests of the keenness and correctness of perception under differing external and internal conditions, and are in constant use for that purpose.

All the methods apply to both extensive and intensive magnitudes. The most convenient stimuli for demonstrational experiments will be found in visual extents and in weights, used either as lifted weights or for pressure. Experiments with the first have the great advantage of seeming less irksome and monotonous; and, if necessary, all three methods can be shown with visual extents alone.

In the fuller explanations that follow, the methods are again considered in their application to difference determination.

237. The Method of Minimal Change. If the student is not already familiar with this method from its application in earlier chapters, it can be tried with pressures, as in Ex. 24 (if possible with the pressure balance, and with attention to the precautions mentioned below), or with visual extents, as in Ex. 174 *b* (where the krypteon may be dispensed with), or indeed with almost any of the experiments given for discriminative sensibility.

Whatever the stimuli selected, the procedure falls into four stages: (1) The determination of the stimulus just observably greater than the standard stimulus; (2) the determination of that just *un*observably greater; (3) the determination of that just observably less; and (4) the determination of that just *un*observably less.

In the first stage, a standard stimulus is applied, and immediately after it another exactly like it (or at least not perceptibly different from it). The subject reports them "the same." The standard is again applied, and after it a slightly greater stimulus, which the subject usually calls "the same" again. Comparison of the standard stimulus with successively greater stimuli is thus continued till one is found which the subject reports as just noticeably greater. The excess of the variable stimulus over the standard is then recorded. The first stage might end here, but it is considered better to increase the variable stimulus once or twice more in order to guard the subject against a merely accidental impression that a perceptible difference has been reached, though no record is made of the differences used unless it is evident that his previous success was accidental. The second stage is like the first, except that it begins with the comparison of the standard with a vari-

able stimulus unmistakably greater, and that the latter is reduced little by little till it just ceases to seem different. The excess of the variable at this point is recorded, and one or two confirmatory trials made as before. The third stage is like the first, except that the variable stimulus is gradually decreased from apparent equality, and the fourth like the second, except that the trials begin with the variable stimulus unmistakably less than the standard.[1]

The records reached in the four stages are subject, of course, to more or less of accidental variation, to avoid which it is necessary to repeat each a number of times, and to average the results. Care must also be taken to avoid certain other sources of error, which will be considered after the arithmetical treatment of the results has been made clear by an example.

Let us suppose that in an experiment with pressures on the finger-tip the standard stimulus has been 25 grams, and that the following differences have been found in the ten trials indicated by the Roman numerals[2]: —

DIRECTION OF CHANGE.	I	II	III	IV	V	VI	VII	VIII	IX	
From equality upward . .	1.0	0.8	0.6	1.2	0.8	0.6	1.0	1.2	0.6	0.6
Toward equality downward .	1.0	0.8	1.4	1.2	1.0	1.2	1.4	1.0	0.6	1.0
From equality downward .	1.4	1.0	1.6	1.4	1.2	1.2	1.4	1.4	1.4	1.0
Toward equality upward . .	2.0	1.2	1.8	2.0	2.0	1.8	1.8	1.4	1.8	0.6

If we take the averages of the ten series for each of the four stages we shall have the following values in grams for

[1] The just observable and just unobservable differences are combined in both cases on the supposition that the subject will tend to report the expected result too soon (or too late), and that the true just observable difference will lie between them.

[2] The figures of this example are but slightly changed from those of an actual experiment with the pressure balance.

the just observable difference or *limen*, with the accompanying mean variations.[1]

	LIMEN.	M.V.
Changing from equality (above)	0.84	0.21
" toward " (above)	1.06	0.19
" from " (below)	1.30	0.16
" toward " (below)	1.64	0.24

Examination of these figures shows first that the mean variations are large in proportion to the averages, and therefore that the determinations are irregular, and in so far uncertain. Disregarding that in this instance, however, let us examine the averages themselves. Averaging the four determinations, we have 1.21 as the average just observable difference (or average limen of difference), the reciprocal of which is taken as the measure of the keenness of the discrimination of the subject under experiment. Stated as a

[1] The mean variation (M. V.) is found by substracting algebraically from the average each of the terms that has entered into the average, and taking the mean of these remainders without reference to sign. Thus the terms of the first line across the table subtracted each from 0.84 give the following remainders: — + 0.16, — 0.04, — 0.24 + 0.36, — 0.04, — 0.24 + 0.16 + 0.36, — 0.24, — 0.24, which averaged without reference to sign gives 0.21 as the mean variation.

A convenient way of checking the correctness of the average and most of the process of finding the mean variation is to keep the plus and minus remainders separate as long as possible. If their sums are the same the work is correct to that point; e.g.: —

+ 0.16, 0.36, 0.16, 0.36 = 1.04
— 0.04, 0.24, 0.04, 0.24, 0.24, 0.24 = 1.04
1.04 + 1.04 = 2.08; 2.08 ÷ 10 = 0.208
approximately 0.21.

Expressing the rule in a formula gives: —

$$M.V. = \frac{(A-a_1)+(A-a_2)+(A-a_3)+\cdots(A-a_n)}{n},$$

in which A is the average, a_1 a_2 a_3, etc., are the individual observations, and n the number of the observations entering the average. In more condensed form the formula stands: —

$$M.V. = \frac{\Sigma v}{n},$$

in which Σ is the sign for summation, v stands for the individual variations of the observations from the mean, and n for the number of observations.

ratio with the standard we have 1.21 : 25, or about 1 : 20; in per cent 4.8. Combining the pairs of determinations above and below the standard, we have 0.95 as the just observable increase of weight (or the upper limen of difference), and 1.47 as the just observable decrease (or lower limen of difference).

It is clear that much greater change was necessary below the standard than above it, though approximate equality might have been expected. This points to a constant tendency toward underestimation of the standard (or overestimation of the variable stimulus) — toward a constant error. This amounts to half the difference of the limens, or 0.26, making the estimated or effective value of the standard: —

$$25 - 0.26 = 24.74.$$

We now return to some of the conditions required in the careful application of the method. The most important of these, after a uniform condition of attention on the part of the subject, is such an arrangement of the tests as will exclude or neutralize all recognized sources of constant errors. Two of these are of such frequent occurrence as to have received special designations; namely, the *Time Error* and the *Space Error*. It is impossible to present both the standard and the variable stimulus to the same sensory surface at the same time; they must be applied at different places or at different times. If, therefore, there is any peculiarity of perception attaching to one place or the other, or to the leading or following position in time order, constant differences will be introduced. In the example above, the space error has been avoided by applying both stimuli to the same finger-tip, but the time error remains unless specially met. This is done by dividing the tests, and giving half in the order described and half in the reverse order — the variable stimulus being applied first and the standard

following. If this had not been done in the example considered, the constant error 0.26 would not be attributable as suggested, but might probably indicate an unexcluded time error. In the visual comparison of lengths the time error is supposed to be avoided, but the space error must be compensated by presenting the standard length at the right of the variable length as often as at the left; and similarly with tests in the fields of other senses. Differences in practice may sometimes be treated in a similar way, but where certainty of result is required, must be excluded by a preliminary course of training. To ascertain whether changes in practice are introducing changes in the results, the records should be divided into sub-groups, and their averages examined.

The time and space errors and the stage of practice must be regarded in the use of all the methods. In the case of the Method of Minimal Change the tests above and below the standard, both working toward it and away from it, must be so alternated as to bring each stage of the test into as nearly like conditions of attention and fatigue as possible; at least, when accuracy is an object. A necessary condition of this method of compensating constant error is that the sets of tests combined shall be of equal extent, and as much alike as possible in all respects except the variation especially intended.

In tests with the Method of Minimal Change the subject is supposed to know the direction in which the variable stimulus is altered, but not the precise amount. He is therefore liable to the effects of expectant attention. Besides the danger of reaching the expected result too soon, which is guarded against by combining the determinations of just observable and just unobservable differences, there is also a certain danger that the responses may after a time become mechanical, and the subject report the limen

after a certain number of applications of the variable stimulus, irrespective of its amount. This may be met by occasional changes from the regular procedure — changing the size of the alterations by which the limen is approached, repeating the standard or one of the intermediate weights, etc. Economy of time and patience dictates that the alterations of the variable stimulus should be large while remote from the limen and small when near it, and that the number should not be so great as to weary the subject before reaching it. The number will of course vary somewhat with circumstances; Külpe speaks of five as an average number. Other precautions will suggest themselves to the careful experimenter as need arises.

The chief criticism passed upon the method is that its criterion of the just noticeable difference is wholly subjective, and will vary with the subject's willingness to risk errors. This is undoubtedly true, but does not rob the method of all usefulness.

238. The Method of Right and Wrong Cases. This method may be tried conveniently with visual extents or lifted weights, and will be illustrated here by both. In applying it, a certain difference of stimuli, known to be generally, but not always, recognizable, is chosen, and the variable stimulus set once for all greater or less than the standard by that amount. The two stimuli are then presented to the subject a large number of times for judgment. Sometimes the greater stimulus will seem greater, sometimes it will be indistinguishable, sometimes it will seem less. On the assumption that these variations are of the same sort as those contemplated by the mathematical theory of errors, methods of calculation have been worked out which give values somewhat analogous to those reached by the Method of Minimal Change, and by which

also it is possible to calculate from the ratio of right judgments and the difference of the stimuli in a given case the difference required to give any other proportion of right judgments under similar circumstances. These so far as they are necessary for the treatment of ordinary results will appear in the following examples.

In the first illustration the method will be followed in its classical form; in the second, in a simpler form recommended by Jastrow, and Fullerton and Cattell.

For the first example, let us suppose that in an experiment with visual extents a standard stimulus of 1.5 inches, and a variable stimulus, different by .03 of an inch, were selected; that two hundred judgments were made, one hundred with the variable stimulus greater, and an equal number with it less; that the standard lay at the right side in one-half of each set, and at the left in the other half, and that the following records of right, wrong, and equal cases were made: —

Standard stimulus, 1.50 inches, variable stimulus, 1.53 inches.

I. Standard Right.		II. Standard Left.	
Right,	31.	Right,	31.
Wrong,	5.	Wrong,	2.
Equal,	14.	Equal,	17.

Standard stimulus, 1.50 inches, variable stimulus, 1.47 inches.

III. Standard Right.		IV. Standard Left.	
Right,	25.	Right,	18.
Wrong,	1.	Wrong,	6.
Equal,	24.	Equal,	26.

The values which this method gives are the measure of precision, commonly represented by h in the formulæ, which is directly proportional to the keenness of discriminative sensibility, and a value for the average limen; or, as it may very well be termed when reached by this method,

the "probable limen" (S), though the trustworthiness of this value is questioned.[1] These may be reached in any special case from the following formulæ and table, D being the difference of the stimuli employed, t_1 the value of t corresponding to the percentage of right cases, and t_2 that corresponding to the percentage of right and equal cases combined.

$$h = \frac{t_1 + t_2}{2\,D} \qquad S = \frac{t_2 - t_1}{t_2 + t_1} \cdot D$$

FECHNER'S FUNDAMENTAL TABLE.[2]

$\frac{r}{n}$	$t = h\,D$	$\frac{r}{n}$	$= h\,D$	$\frac{r}{n}$	$t = h\,D$	$\frac{r}{n}$	$t = h\,D$	$\frac{r}{n}$	$t = h\,D$
.50	.0000	.60	1791	.70	.3708	.80	.5951	.90	.9062
.51	.0177	.61	1975	.71	.3913	.81	.6208	.91	.9481
	.0355	.62	2160	.72	.4121	.82	.6473	.92	.9936
	.0532	.63	2347	.73	.4333	.83	.6747	.93	1.0436
.54	.0710	.64	2535	.74	.4549	.84	.7032	.94	1.0994
.55	.0890	.65	2725	.75	.4769	.85	.7329	.95	1.1631
.56	.1068	.66	2917	.76	.4994	.86	.7639	.96	1.2379
.57	.1247	.67	3111	.77	.5224	.87	.7965	.97	1.3297
.58	.1428	.68	3307	.78	.5460	.88	.8308	.98	1.4522
.59	.1609	.69	3506	.79	.5702	.89	.8673	.99	1.6450
								1.00	∞

In the example, when the standard was at the right and the stimuli were 150 and 153 (taking 0.01 inch as the unit for convenience in calculation), the number of right cases was 31, and of equal 14, or in per cent. 62 and 28. The

[1] From h also may be reckoned the "probable error" (see below, p. 359, note) to which it stands in a fixed relation; namely,

$$p.e. = \frac{0.4769}{h}.$$

Külpe (p. 69) defines S as "that stimulus difference which is just as often cognized (correctly judged) as not cognized (incorrectly judged)."

[2] Condensed from Wundt's "Physiologische Psychologie," 4te Aufl., I., 350.

value of t for 62% is found in the table as 0.2160, and that for 90% (i.e., 62 + 28) as 0.9062. Substituting these values for t_1 and t_2 in the formula for h, and dividing by $2\,D$ (= 6), we have $h = 0.19$. Substituting in the formula for S we have 1.85. Applying the same formulæ in the case when the standard was at the left gives the values $h = 0.24$; $S = 2.11$. In the third case (stimuli 150 and 147, standard right), the only difference is that the percentage of right cases is only 50, and consequently $t_1 = 0$. The values of h and S are: $h = 0.27$; $S = 3$. In the fourth case (standard left), the number of right cases is only 18. This shows the presence of a constant error of greater amount than the difference used. The effective value of the standard stimulus is less than that of the variable. The values of h and S may be calculated, however, by taking the percentage by which the right cases fall short of 100, and using $h\,D$ as a minus quantity. In this case 18 right judgments are 36%; 100 − 36 = 64, the value of t for which is 0.2535, or here $t_1 = -0.2535$. The value of t_2, found in the usual way, is 0.8308, which substituted in the formulæ with t_1 gives: $h = .10$; $S = 5.63$.

It is clear that not only in this last case, but in the others also, there is a constant error, and consequently that the values of h and S are not what they should be. It was with the elimination of these in view that the conditions were varied, both as to the position of the standard and the size of the variable stimulus, in such a way that both influences should be opposed to themselves in an equal number of cases. The average result is therefore nearer right than any of the individual ones. Averaging gives $h = 0.20$, $S = 3.15$. Expressed in a formula, this process stands: —

$$h = \frac{T_1 + T_2 + T_3 + T_4}{4\,D},$$

T in this case representing the combined $\frac{t_1 + t_2}{2}$ of previous formulæ.

By similar formulæ the values of the two constant errors allowed for in the arrangement of the tests may be found. If we let C' represent the constant tendency which increases the apparent difference when the standard lies at the right, and C'' the tendency which increases the apparent difference when the standard is compared with a larger variable (150 with 153), it is clear that in Group I. both C' and C'' will be positive; in Group II., C' will be negative and C'' positive; in Group III., C' positive and C'' negative; and in Group IV., both C' and C'' will be negative. From these relations are derived the following: —

$$C' = \frac{T_1 - T_2 + T_3 - T_4}{T_1 + T_2 + T_3 + T_4} \cdot D$$

$$C'' = \frac{T_1 + T_2 - T_3 - T_4}{T_1 + T_2 + T_3 + T_4} \cdot D$$

Making the calculation in this case gives $C' = 0.46$ and $C'' = 0.22$.[1]

The Method of Right and Wrong Cases in its Simpler Form. Much complexity is introduced into the classical form of the method by the cases which the subject pronounces "equal." In the simpler form advocated by Jastrow, and Fullerton and Cattell, all these are avoided by requiring the subject to indicate one or the other of the stimuli each time as greater, and in case of complete uncertainty to guess. The resulting record contains right and wrong judgments only. From the percentage of right

[1] The data of this example are the records of an actual experiment, made, however, under not altogether constant conditions, and not such as would favor great accuracy. They serve, however, well enough for illustrating the method of calculation. Under favorable circumstances h might be expected to be larger and S smaller.

cases, taken in connection with the difference of the stimuli employed, the amount of difference required to give 75% of right judgments is calculated. This is regarded as the value of the average or probable limen, and its ratio to the standard used like that of the limen in the Method of Minimal Change as the measure of the keenness of sensibility. The selection of 75% is of course arbitrary, but it has certain recommendations. It lies midway between the proportion of cases right by pure chance (50%) and the proportion right in case of full certainty, and corresponds also to the value of the "probable error" in the probability curve. To facilitate this calculation, Fullerton and Cattell give the table below.[1]

TABLE FOR DETERMINING THE PROBABLE ERROR FROM THE PERCENTAGE OF RIGHT CASES AND AMOUNT OF DIFFERENCE.

%r.	$\frac{D}{p.e.}$	%r.	$\frac{D}{p.e}$	$\frac{D}{p.e.}$	%r.	$\frac{D}{p.e.}$	%r.	
50	.00	60	.38	.78	80	1.25	90	1.90
51	.04	61	.41	.82	81	1.30	91	1.99
52	.07	62	.45	.86	82	1.36	92	2.08
53	.11	63	.49	.91	83	1.41	93	2.19
54	.15	64	.53	.95	84	1.47	94	2.31
55	.19	65	.57	1.00	85	1.54	95	2.44
56	.22	66	.61	1.05	86	1.60	96	2.60
57	.26	67	.65	1.10	87	1.67	97	2.79
58	.30	68	.69	1.14	88	1.74	98	3.05
59	.34	69	.74	1.20	89	1.82	99	3.45

The use of the table will appear in the following example taken from their records (p. 121). The experiments

[1] It is obvious from the relation between the probable error and the quantity h already mentioned $\left(p.e. = \frac{0.4769}{h}\right)$ that this table can be made out by dividing the corresponding values of Fechner's table by 0.4769.

were on the discrimination of lifted weights. In a set of 50 trials, when the weights used were 100 and 104 grams, and the heavier weight was lifted first, the subject R made 36 right judgments and 14 wrong; in an equal number, with the same weights lifted in the reverse order, the right judgments were 28 and the wrong 22, or in percentage 72% right with the standard following, and 56% right with the standard leading. Referring to the table, we find for $\frac{D}{p.e.}$ in the first instance 0.86, which means that in order to give the proportion of 75% of right judgments the difference (4 grams) would (probably) have to be increased in the ratio of 0.86 : 1; that is, to 4.65 grams — this, however, only in case the heavier weight comes first. When it came last the percentage of right judgments was 56, which corresponds in the table to 0.22; and the difference would have to be increased in the ratio of 0.22 : 1, that is, to 18.18 grams. There is then a strong tendency toward underestimation of the second weight.[1] This can be eliminated, however, in a manner similar to that indicated in the previous example. Representing the constant error by C, the $\frac{D}{p.e.}$ in the first case would really be $\frac{D+C}{p.e.}$, and in the second case $\frac{D-C}{p.e.}$. Adding these fractions eliminates C, giving $\frac{2D}{p.e.}$, from which it is easy to get the D required for 75% right judgments. $0.86 + 0.22 = 1.08$ and $1.08 \div 2 = 0.54$, which gives 7.4 grams as the amount required when constant errors are excluded. This is the average limen, and the sensibility of the subject may be expressed by its reciprocal, $\frac{1}{7.4}$, or by its ratio to the standard, 7.4 : 100.

If the value of the constant error (in this case the time

[1] With most of Fullerton and Cattell's subjects the tendency was in the other direction, and that would appear to be the common tendency.

error) is desired, it can be calculated after the same analogy.

$$\frac{D+C}{p.e.} - \frac{D-C}{p.e.} = \frac{2\,C}{p.e.}.$$

In this instance $\frac{2\,C}{p.e.} = 0.86 - 0.22 = 0.64$. $\frac{C}{p.e.} = 0.32$. It has just been found that $\frac{D}{p.e.} = 0.54$, whence $p.e. = \frac{D}{0.54}$ and $C = \frac{0.32}{0.54} \cdot D = 2.37$. The elimination of several simultaneous constant errors would of course be the same in principle, but the experiment would have to be planned with that in view from the start.

It remains to speak of a few points with regard to the actual use of the method in both its forms. The first requisite is a large number of tests; the formulæ are not very reliable when the numbers are small. If long series are fatiguing, several shorter series taken under like conditions may be combined. Such a difference between the stimuli must be chosen if possible as will give neither too great nor too small a number of right judgments — about eighty-five in a hundred is recommended by Fullerton and Cattell. It is therefore profitable to make preliminary determinations by one of the other methods before undertaking systematic experiments by this.

The method has been used when the subject had full knowledge of the actual relation of the stimuli (when he was himself the operator), but this usage is less to be recommended than that in which the subject is in complete ignorance. This is absolutely essential, indeed, in the simpler form of the method.

The subject's task is simply to judge of the stimuli presented to him, the operator's to present the stimuli as uniformly as possible. In the simpler form of the method the subject will be assisted in his selection of one or the

other as greater by a clear understanding that he is never to be presented with equal stimuli.[1] He must also feel sure that one arrangement is as likely to be given as the other, lighter-heavier as likely to occur with weights, for example, as heavier-lighter. In short series the subject is apt to be influenced by his recollection of how often his answer has fallen one way or the other; but this can be met by longer series, or by short series so arranged that the number of times each arrangement occurs shall not be the same in each series, but that the final combined record shall show an equal number of tests made with each arrangement.[2]

It is not always convenient to present a standard stimulus with two variable stimuli, one larger and one smaller, as was done in the example with visual extents, and sometimes it entails great waste of time. It is advisable, therefore, in ordinary experiments to carry out the testing with two stimuli only, letting the greater serve as the standard when experimenting for the determination of the probable limen below, and the less when experimenting for that above, as in the second example. For other suggestions and precautions, see Jastrow, *B.*

239. The Method of Average Error. This method is applicable to any stimuli that can be put, directly or indirectly, under the control of the subject; it is most convenient when the control is direct and simple. These conditions are fully met in the case of the comparison of lengths by vision; for example, in experiments with the

[1] If for any reason a few doubtful answers cannot be avoided, they may be divided equally between the right and wrong judgments without serious error, but it is better not to allow them at all.

[2] A similar difficulty is met in the case of large constant errors which throw a marked proportion of the judgments in one direction or the other. This is more difficult to deal with, but might be helped by a special combination of series with stimuli of different degrees of difference.

Galton bar, or with narrow strips of millimeter paper, cut through with a knife point.[1] The application of the method is so simple that it may be easily understood from a single example. One slide of an instrument somewhat like the Galton bar was set at a standard distance from the centre line of 1.50 inches. The instrument was then handed the subject, with the request that he set the other slide at exactly the same distance from the line. When he had done so the instrument was examined, his setting recorded, the slide displaced, and the whole process again repeated. Forty trials were made, in half of which the standard distance lay at the right, and in half at the left. In half the trials in each position, also, the movable slide was too far from the centre line when the instrument was given to the subject, and in half it was too near. The following settings were regarded by the subject as equal to the standard of 1.50 inches. The unit in the table and in subsequent calculation is taken for convenience as 0.01 inch.

STANDARD LEFT.		STANDARD RIGHT.	
FROM TOO SMALL.	FROM TOO LARGE.	FROM TOO SMALL.	FROM TOO LARGE.
147	145	144	147
145	145	149	148
145	150	145	146
147	148	148	151
149	149	150	146
145	151	148	151
149	149	146	150
142	150	149	156
147	151	147	149
151	144	146	147

[1] These strips may be 200 mm. long by 5 mm. wide. When in use they are presented to the subject with the blank side of the strip uppermost, and he is

The average of these forty trials is 147.8, showing a constant error of 2.2; that is, the extent made by the subject fell 2.2 short on the average, or, in other words, he overestimated his setting each time by that amount on the average. The mean variation of the single settings from the average, found as explained above, is 2.11, the average limen (S) as given by this method. Its reciprocal $\frac{1}{2.11}$ is the index of the keenness of sensibility. Expressed as a ratio, it is 2.11 : 150, or about 1 : 71; in per cent. of the standard 1.41.[1]

If we take the groups separately we can find the effect of the special conditions to which each was submitted. The averages are as follows:—

STANDARD LEFT.		STANDARD RIGHT.	
From too small	146.7	From too small	147.2
From too large	148.2	From too large	149.1

Combination of these shows that the average setting when the standard was at the left was 147.45, and when

asked to indicate by a sharp cut with the point of a penknife the exact middle of the strip. The strip is then turned over, and the displacement of the cut from the exact centre is easily read in millimeters and (by estimate) to tenths of a millimeter.

[1] The mean variation is not the only quantity which can be taken as the limen by this method; the average error, and the probable error of a single observation may both serve that purpose. The average error is not to be confused with the average (or mean) variation, the two standing to one another in the following proportion:—

$$\text{M. V.} : \text{A. E.} :: 1 : 1.2533.$$

The probable error of a single observation is given by the formula

$$p.e. = 0.6745\sqrt{\frac{\Sigma v^2}{n-1}},$$

or approximately by the formula:—

$$p.e. = \frac{0.8453\,\Sigma v}{\sqrt{n(n-1)}}.$$

in which Σ, v, and n have the same significance as before.

Its relation to the mean variation is roughly:—

$$p.e. : \text{M. V.} :: 0.85 : 1.$$

at the right, 148.15. Half of the difference between these two is 0.35, and is the amount fairly to be credited to the space error, — the amount by which, on the average, the subject overestimated the variable extent when comparing it with a standard of 150 lying at the left.

Combining the series in which the direction of the movement of the slide was different, we get an average of 146.95 when the slide was too near at the start, and 148.65 when it was too far away. The subject evidently tended to stop too soon in the moving in both cases, and by an amount equal to half the difference of these averages, namely, by 0.85, — a space error of another kind, and in this instance a more important one.

The constant error of the general average (2.2), which remains in spite of the combination of all four groups, indicates the action of some other unneutralized cause, and, if all other influences have been certainly avoided, to some peculiarity of the subject's method of estimate.[1] To determine whether the cause of the constant error lies in some truly constant tendency, or in mere accident (as it may when the number of trials is small), the probable error of the average (147.8) must be calculated.[2] If the constant

[1] This example, like those before, is the record of an actual experiment. Unfortunately the data are not sufficient to exclude the possibility that at least a part of this 2.2 may be of instrumental origin. The ratio of the general limen to the standard (1 : 71) is larger also than is usually expected in experiments of this kind.

[2] The probable error of the average is calculated according to the following formula: —

$$p.e. = 0.6745 \sqrt{\frac{\Sigma v^2}{n(n-1)}}$$

For such use as is here contemplated, the approximate formula: —

$$p.e. = \frac{0.8453 \ \Sigma v}{n\sqrt{n-1}} = \frac{0.8453}{\sqrt{n-1}} \cdot M.V.$$

will answer every purpose.

Merriman's Method of Least Squares, from which these and several of the preceding formulæ are taken, also contains tables by which the calculation of the probable error is much facilitated.

error is distinctly larger than the probable error of the average, it may be assumed to represent a true tendency, and not an accident. In this instance the probable error is 0.28.

The Method of Average Error and the Method of Right and Wrong Cases are both founded on the assumption that the principle of probability applies to the small uncertainties or variations of perception. The results obtained by them ought, therefore, to be comparable, and, provided the conditions are the same, not greatly different in amount. A difference in result would therefore point to a difference in conditions, and, external conditions being the same, to those of a subjective character. The two experiments with visual extents, used as illustrations above, were made with the same subject and same apparatus, and may serve for illustration of this point also. There are two quantities among the results that may be used for comparison: the difference required for 75% of right judgments, which should be the same as the probable error, and the measure of precision, the quantity h of the formulæ.[1] By the Method of Right and Wrong Cases we had $h = 0.20$, giving *p. e.* 2.38. By the Method of Average Error we have $h = 0.26$, and *p. e.* 1.81, showing a finer discrimination in the latter case, which in this instance may well correspond to a higher grade of attention.

Of special precautions in the use of this method little need be said. The subject should, of course, remain in ignorance of the amount and nature of his errors. The groups of tests should be so arranged as to compensate constant errors. The variable stimulus should be made to approach equality an equal number of times from both above and below, especially when the control of it is indirect and the subject must order changes made instead

[1] The constant errors, so far as they arise from the same causes, might also be compared. The probable error above referred to is, of course, the probable error of a single observation.

of making them himself. The number of tests will vary with the purpose of the experiments. The formulæ for the probable error apply more exactly as the number of observations increases, but the number necessary in this method is much less than in the Method of Right and Wrong Cases. The method has very great practical advantages in the simplicity of its procedure and in requiring discrimination not by itself alone, but in its natural relation to action.

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CHAPTER IX.

Suggestions on Apparatus.

The aim in the foregoing chapters has been, almost without exception, to work with the simplest and least expensive apparatus that gave promise of bringing out the essential phenomena of the experiment. That the apparatus used has always been the best, even from this standpoint, is far from the writer's conception. Some apparatus must be used, however, and the following suggestions are offered for what they may be worth.

It is assumed that most of the simpler pieces, especially those of paper and cardboard, will be prepared in the laboratory, and that the more difficult and complicated pieces will be bought outright, or made by a skilled mechanic. Where specifications are given, they are for the most part taken from the pieces actually used in the Clark laboratory, except where decided improvements have suggested themselves. This is done to make the descriptions as definite and helpful as possible; but improvements in construction may frequently suggest themselves to the reader, and ought not to be disregarded.

Apparatus for Chapter I., on the Dermal Senses, Experiments 1–32.

In the way of general apparatus and supplies will be needed a millimeter scale, a cane or light rod, a bit of metric cross-section paper, vessels and means for heating water, two large vessels of the same size and shape, some

bits of cork, a piece of ice, court-plaster, a little ether, a menthol pencil, and three thermometers (preferably centigrade).

Of special apparatus will be needed a compass æsthesiometer, an ether spray, a tuning-fork (see apparatus for Sensations of Hearing), temperature-spot seekers, apparatus for making CO_2, a centigrade thermometer, reading in tenths of a degree between zero and 55°, weights for minimal pressure and for discriminative sensibility, equal weights of unequal size for pressure, wooden cylinders of equal weight, and an algometer.

The *Compass Æsthesiometer.* — An instrument of this sort has long been used by physicians and others, and a good many forms are in the market. An ordinary pair of carpenter's compasses, to be had at a low price at any hardware store, will answer fairly well, the separation of the points being measured with the millimeter scale when required. Drawing dividers can also be used, but are rather sharp, and will serve better if tipped with pointed bits of cork. A more accurate and convenient pair may readily be made by a slight alteration of some of the callipers or calliper squares, to be found in the hardware stores, or in the lists of the dealers in physical instruments.[1]

For the *Ether Spray* any cheap atomizer will answer.

Simple *Temperature-point Seekers* are easily made by turning down round brass rods (six inches long and a quarter of an inch in diameter) to a fine smooth point (0.5 mm. in diameter). Large wire nails may be used.

On *Apparatus for making CO_2* consult any text-book on chemistry.

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[1] For more elaborate and exact apparatus, see Jastrow [A new æsthesiometer], *American Journal of Psychology*, I., 1887–88, 552, and Margaret Floy Washburn, *ibid.*, VI., 1893–95, 422.

The *Thermometer reading to* 0.1° can be had of dealers in chemical supplies.

Weights for Minimal Pressure. — These can be cut from rectangular prisms of cork or elder-pith of equal end area, and provided with bristle or hair handles, and verified upon a sensitive balance. The prism should be about 5 mm. square. The handle is made by setting the ends of a piece of bristle or hair into opposite sides of the bits of cork or elder-pith, thus giving the whole something the shape of a seal ring, of which the cork is the seal and the bristle the band. A series ranging from 2 to 20 mg. would be convenient. Such a series, using paper disks instead of pith, has been prepared by Willyoung of Philadelphia, after the design of Dr. Scripture.

Equal Weights of Unequal Size can easily be made from a large cork and a small one, by hollowing out the small one and loading it with lead. Cf. similar apparatus in the section on Chap. II.

Weights for Testing Discriminative Sensibility with Pressures are to be had in different forms from the dealers. A set can be made in the laboratory without great difficulty by loading shotgun cartridges with shot, as suggested by Galton. Cf. the set for testing discriminative sensibility with lifted weights in the section on Chap. II.

For the *Wooden Cylinders* used in Ex. 25 *b*, bits three-quarters of an inch long, cut from the end of a broom-handle and made smooth on the ends, and of equal weight, would probably answer as well as anything.

An Algometer is not necessary for the experiments described, but has now become a well-recognized instrument in anthropometric studies of sensibility, and may be had from the dealers. The common one in this country is that devised by Prof. Cattell, which works on the principle of an inverted spring balance.

Apparatus for Chapter II., on the Kinæsthetic and Static Senses, Experiments 33–51.

Of general apparatus for this section there is little additional, except a meter stick, a straw, and a couple of small pieces of cotton cloth.

Of special apparatus the following are needed: A large weight, equal weights of unequal size (for lifting), weights for testing discriminative sensibility with lifted weights, a joint-sense board, a tilt-board, and a rotation table.

Any *Large Weight* that can be conveniently handled would answer. For use in the Clark laboratory, cylindrical weights of cast-iron, three inches long and two in diameter, have recently been made and are satisfactory. They weigh between two and three pounds, and serve very well instead of the two kilogram weight mentioned in Ex. 35. If bored and tapped so that a screw-eye could be inserted in the middle of the top, they would be convenient for Ex. 43.

The *Equal Weights of Unequal* size mentioned above also give the illusion in question here. If for any reason it is desired to have the difference of size in one dimension only, a set can easily be made by cutting down paper cartridges, and then loading the shorter ones till they equal the longer in weight. A set of three — full length of the cartridge, two-thirds length, and one-third length — is convenient. In making these it is well to put corks in the longer ones, in order to support the wads with which all are closed. These cartridge weights will not do well for Ex. 23. Special apparatus for this illusion has been devised by Dr. J. A. Gilbert, and is to be had under the name of "Suggestion Blocks."

Weights for Discriminative Sensibility in the case of lifted weights. For this test also special sets have been

made and are in the market. Weights are easily made, however, from cartridges, as before. It would be well to make the set large enough to furnish the differences required for Ex. 24, as well as the finer ones for Ex. 34. A series of weights, increasing by single grams from 80 to 120 grams, and by twos from 60 to 80, and as far above 120 as the cartridges will permit, and containing two 100 gram weights, ought to answer every purpose. A much smaller set will do if, instead of keeping the standard at 100 grams all the time, a standard at the upper end of the series is taken when experiments are to be made below the standard, and one at the lower end when experiments are to be made above the standard. For Ex. 34 the weighted envelopes of Ex. 236 might be used, but they would not do for Ex. 24. In making the weights, it is well to have all seem equally filled (which may be done by using cotton as part of the filling in the lighter cartridges), and to so distribute the cotton or other light substance that the cartridge will not have all the weight at the bottom. The first point is not essential if the subject's eyes are closed during the experiment; and the second is unimportant, except perhaps with the lighter weights, if they are lifted in a vertical position.

Joint-Sense Board. — The cut accompanying Ex. 39 will give some idea of the construction of the joint-sense board. The thin board on which the fore-arm rests is 50 cm. long by 8–10 wide, and is hinged at one end to the base-board. At the other end a cord is fastened, which runs over a pulley upon the top of a stout post. On the end of the cord a weight is hung to counterbalance the weight of the fore-arm. A scale (e.g., a piece of millimeter paper) on the post near the weight enables the experimenter to read off the distance which the end of the arm-board is raised or lowered. It is essential that the hinge and pulley work easily and without jar.

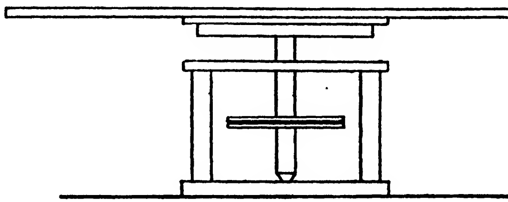
Tilt-Board. — For part of the experiments with the tilt-board, a plank seven feet long and eighteen inches wide, balanced across a saw-horse, will answer. For others a more permanent structure is necessary; e.g., a board permanently hinged across a stout horse three feet and a half or more in height, and with wide-spreading feet. (For cut, see Ex. 46.) If the top piece of the horse is not too thick, and the board is fastened on with hinges such as are used for doors that swing both ways, it will be possible to get all required positions of the subject, from head upward to head downward, without the trouble of mounting the board on an axis. At one end of the long board a short foot-board should be fastened securely enough to bear the weight of a man when the board is in a vertical position. At the other end a plumb-line and semi-circular scale should be added, so that the inclination of the board can be read off at any instant. For holding the subject securely upon the board when its inclination is considerable and the subject is head downward, it will be necessary to have a couple of straps passing over the subject's shoulders and fastening to stout screw-eyes screwed into the board itself or into the foot-board, and perhaps a breast strap going about both the subject and the board.

Rotation Table. — A table, made by fastening a seven-foot plank across an ordinary turning-chair or screw-stool without a back, could probably be made to serve for some of the experiments. The apparatus must turn without appreciable noise or jar. Many of the experiments could be made by twisting the ropes of a swing.

The accompanying cut shows the plan of a permanent piece devised by Aubert.[1]

[1] *Physiologische Studien über die Orientierung, unter Zugrundelegung von Yves Delage Études*, etc., p. 50.

The plan is on a scale of about one twentieth. The table top rests on a central spindle of steel, the lower end of which fits into a shallow socket in the lower part of the iron supporting-frame, two of the three columns of which



are shown in the plan. This central spindle also carries a grooved wheel. The table is turned by means of a driving-cord, which passes around this wheel, and a small drum, not shown in the plan, which is turned by hand. Aubert reports the instrument a very satisfactory one with regard both to ease of motion and freedom from jar.

The rotation table in the Clark laboratory differs from this in being constructed entirely of wood (the supporting-frame having four posts instead of three), and in the omission of the grooved wheel. The direct turning by hand, which is thus required, is of course less satisfactory than turning by a driving-cord, but answers for the experiments described in the text. The ends of the table top are rounded, the curve having a radius equal to half the length of the table. On these a scale of degrees might well be laid off, so that a rough judgment of the angular rate would be possible.

Apparatus for Chapter III., on Sensations of Taste and Smell, Experiments 52-60.

For taste experiments the following general apparatus is necessary: four or more camel's-hair pencils, a mirror,

and a battery. For the latter, see the section on General Apparatus.

Of special apparatus: a little essence of clove, materials for making the various test solutions, and a pair of small zinc electrodes.

The *Essence of Clove* is for the demonstration of the habitual associations of taste and smell (Ex. 52). The same can be shown even more conveniently with small Dennison labels, the gum of which is flavored with sassafras. They may be had at almost any stationer's, and being dry are more convenient to handle than the clove solution. For proportions of oil of clove and alcohol in this essence, see the "essence of clove" mentioned below among the materials for experiments on smell.

The *Solutions* should be made of two strengths, — the stronger for testing the individual papillæ, and the weaker for finding the general taste areas and the least proportion tastable. The following proportions of tastable substances and water are convenient. Stronger solutions: Sugar, 40 : 100; Quinine, 2 : 100; Tartaric Acid, 5 : 100; Salt, saturated solution. Weaker solutions (for which the water itself should be without taste): Sugar, 5 : 100; Quinine, 2 : 100 000; Tartaric Acid, 5 : 1 000; Salt, 2 : 100. Special solutions of Sugar for Ex. 55 : 20 : 100, 18 : 100, 16 : 100, 14 : 100, 12 : 100, 10 : 100.

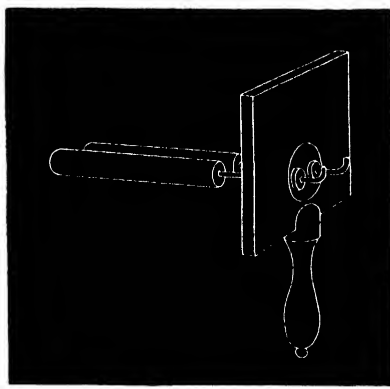
The *Zinc Electrodes* can be made by soldering bits of sheet zinc an inch and a half long and half an inch wide to pieces of ordinary covered copper wire of convenient length.

For experiments on smell the following will be required: essence of clove, an olfactometer, camphor gum, yellow wax, a dozen small wide-mouthed bottles.

The *Essence of Clove* is made by adding one part of oil of

cloves to fifteen parts of alcohol,[1] and may be diluted with water, itself odorless, to make the solutions required in Ex. 57 *a*. For that experiment dilutions of the essence that will give the following proportions of oil of cloves will be convenient: 1 : 50 000; 1 : 100 000; 1 : 200 000; 1 : 300 000; 1 : 400 000; 1 : 500 000.

A number of *Olfactometers* of different form have been suggested by different experimenters. The olfactometer of Zwaardemaker is so simple in construction that it may be made in the laboratory. It will be most convenient if made double, as shown in the accompanying cut.



The instrument consists of a light wooden screen, say six inches square, provided with a handle below for easier holding. Through this screen, a little below the middle, a hole an inch and a half in diameter is bored, and fitted with a large cork. The cork in turn is pierced with two holes side by side, an inch apart, and of such size as to fit tight upon the glass tubes next to be mentioned, i.e., about 7mm. The glass tubes should be long enough to leave 10 cm. free behind the screen, and about 3 cm. free in front. The front ends are bent upward at right angles for insertion in the

[1] Whether this essence is of the same strength as that used by Lombroso and Ottolenghi in their experiments, to which reference is made after Ex. 57, the writer does not know.

nostrils. The odorous substances are applied in the form of tubes that slide over the glass tubes behind the screen. The simplest and best for persons of normal keenness of smell are said to be pieces of red rubber tubing 10 cm. long, and of such bore as just to slide freely over the glass tubes (8mm.). These pieces of rubber tubing should themselves be slipped into pieces of tight-fitting glass tubing, so as to prevent the spread of the odor from their outer surface. For Ex. 60 another odor-tube, this time of yellow wax, will be needed. This can be made by placing a glass tube (of the size of the air-tubes used in the olfactometer) inside a tube such as is used to cover the rubber odor-tubes, and filling the space between them with melted wax, and afterward withdrawing the inner tube.

The assumption upon which the instrument is constructed is that the intensity of the odor varies directly as the surface of odorous substance exposed. When the odor-tubes are slipped upon the glass tubes of the olfactometer, and pushed back until their ends are flush with those of the glass tubes, the air inhaled through the latter contains few or no odorous particles, because no odorous surface is exposed. When, however, the odor-tubes are pulled a little away from the screen, so that they extend over the ends of the glass tubes, they expose the odorous surface inside them to the current of air inhaled. The strength of the odor is proportional to the length of odor-tube that extends beyond the glass tube. The length of odor-tube corresponding to a just observable odor will, of course, differ with different tubes, from person to person, and with the temperature; but tubes of red rubber are reported to give satisfactory results, both as to original intensity, and the constancy with which they keep their odor through considerable periods of time. The length of red rubber odor-tube required by Zwaardemaker himself for a just

observable odor at 18° C. is 7 mm. In use the upward turned end of one of the glass tubes is inserted in the forward part of the nostril, and the subject draws his breath in the way most natural to him in smelling; the proportion of odorous particles is greater, however, when the current of air is slow than when it is rapid. The inside of the glass air-tubes may need to be cleansed of adhering odorous particles from time to time. Zwaardemaker's olfactometer is also made in a more perfect form, having porous earthenware cylinders which will absorb odorous substances for testing. On this and other related matters see his "Physiologie des Geruchs," Leipzig, 1895. An olfactometer on somewhat the same principle, but of different form, made after the design of Dr. Scripture, is also to be had.

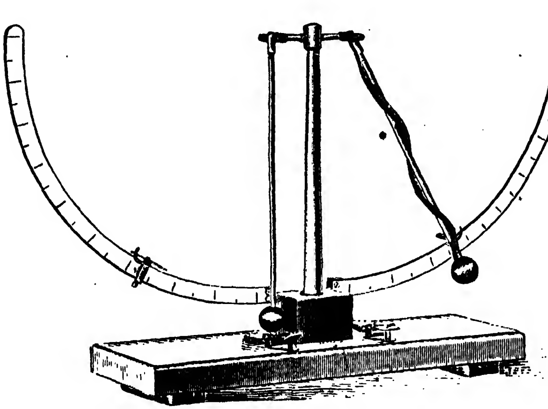
Apparatus for Chapter IV., on Sensations of Hearing, Experiments 61–103.

Of general apparatus the following will be required: a small package of absorbent cotton, three yards of rubber tubing (one-quarter inch outside measurement), a pint bottle, and an ordinary clock.

Of special apparatus: a sound pendulum, a pendulum carrying a small tuning-fork, a rubber hammer for striking tuning-forks, low-pitched forks (or Appunn's lamella), several forks on resonance boxes, a set of mistuned forks for just noticeable difference in pitch, various small tuning-forks, a sonometer, a set of resonators, two or more piston whistles, Galton whistle or steel cylinders for highest audible tones, two or more bottle whistles, apparatus for blowing hydrogen bubbles, and a "snapper sounder."

The *Sound Pendulum* represented on the following page was made with slight modifications from the instrument

described by Kämpfe, and pictured also in Wundt ("Physiologischen Psychologie," 4te Aufl. I., 361).[1]



The sound is produced by the stroke of the balls at the end of the pendulum rods against an ebony block, and is assumed to vary in intensity in direct proportion to the height of the fall, or to the square of the sine of half the arc through which the pendulum swings.[2] The following table is calculated, after that of Kämpfe (p. 534), to show the proportional intensity of sounds produced by falls between 30° and 50°, the sound at 40° being taken as unity.

In use the pendulum rods need to be wrapped with something to prevent the short tone that they give after the blow, which interferes with the judgment of the sounds. Kämpfe and Wundt mention wrapping with felt, and

[1] Though the instrument here appears with two pendulums and two arcs, one with a single pendulum and arc was preferred by Kämpfe, and would be both cheaper and better.

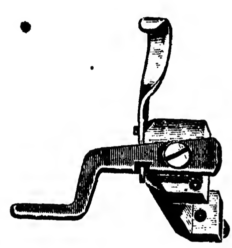
[2] For the justification of this assumption, see Kämpfe, *Wundt's Philos. Studien*, VIII., 1892-93, 526 ff.

Kämpfe found it necessary to wrap the free end of the arc with the same material. A winding of small rubber tubing, as shown in the cut, seems tolerably deadening. The keys on either side of the ebony block are covered with felt, and were intended to catch the pendulum as it returns after its first recoil, and so prevent repetitions of the sound. The same can be done, however, as conveniently with the hand.

Table of relative intensities of sounds when the sound pendulum falls through any angle between 30° and 50°, the sound at 40° being taken as unity.

Angle.	Intensity.	Angle.	Intensity.	Angle.	Intensity.
30°	0.57	37°	0.86	44°	1.20
31	0.61	38	0.91	45	1.25
32	0.65	39	0.95	46	1.31
33	0.69	40	1.00	47	1.36
34	0.73	41	1.05	48	1.41
35	0.77	42	1.10	49	1.47
36	0.82	43	1.15	50	1.53

For demonstrational purposes the pendulums might also be released from the fingers. For more exact tests a mechanical release is preferable. That attached to the Clark instrument is pictured in the accompanying cut.



The release is shown as it would appear if looked at from a point about half-way up the central column of the instrument. The rod of the pendulum rests against the bent portion at the left end of the crossbar. The latter turns easily about the screw by which it is fastened to the clamp, by which, in turn, the whole is fastened to the arc of the instrument. The curved piece, standing vertical

in the cut, is provided with a little hook at its lower end, which holds the crossbar till it is desired to release the pendulum, when by a slight upward pressure (that is, by a movement toward the observer when the release is seen as in the cut), the hook is drawn away, the crossbar turns, and the pendulum falls. The clamp is held in place on the arc by a set-screw below. It is essential, of course, that the release work as easily and with as little noise as possible.

Though the instrument is one that probably would be bought ready made, the following dimensions given by Kämpfe may be convenient to some: base-board, of oak, 45 cm. long, 15 cm. broad, 3 cm. thick; central column (steel), 33 cm. high, average diameter, 2 cm.; cross-piece at the top of the column, 8.5 cm. long and 1 cm. in diameter; length of pendulum rods (wood), 30 cm.; diameter of balls of pendulum (hard rubber), 3 cm.; striking-block (ebony), 7 cm. long, 5 cm. broad, and 6 cm. high. This is glued to the base instead of being fastened with screws; and the hole in it is made so large that it does not touch the central column, in order to secure as uniform and uncomplicated sounds as possible. The pendulums swing on points. The arcs in Kämpfe's instrument were divided to single degrees, and in some parts apparently even to tenths of a degree. For general use single degrees would certainly be fine enough. The whole instrument is supported upon thick pieces of felt to prevent any possible resonance of the table on which it is used.[1]

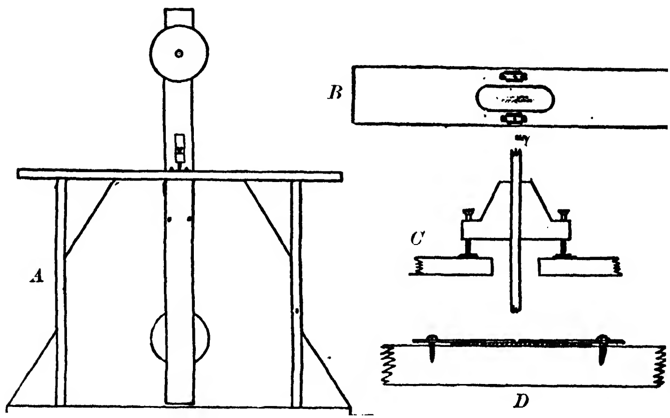
When the instrument is to be used, it should be so ad-

[1] In the instrument in the Clark laboratory, the chief differences are in the shape of the ebony block, which is a complete parallelopiped, and the consequent change in the length of the upper cross-piece, and of the separation of the short posts from which the arcs spring. The central column is also a little taller and the pendulums a little longer. The arcs are divided at intervals of 5 and 10 degrees, the intermediate degrees having to be judged by eye.

justed that the pendulums swing freely and the balls, when at rest, just touch the ebony block.

Pendulum for Carrying a Small Tuning-fork. — Any convenient pendulum can be used for this purpose. That described below, though rude in construction, has proved useful for this and other purposes.

The general plan of the instrument is shown in the cuts below. *A* shows the face view, and *B* the top board by



itself; *C* and *D* show, on different scales, the screws on which the pendulum swings and the sockets that receive them. The rod of the pendulum is of wood, three and a half feet long, three inches wide, and half an inch thick. The bobs are composed of several six-inch disks of sheet lead, superposed and fastened to the rod with a single screw through the centre. The screw of the upper disk has a milled head, so that it may be more easily removed for altering the position of that bob. The lower bob is fixed permanently with its centre seven inches from the end of the rod. The position of the upper bob, shown in *A*, makes its centre

come four and three-quarter inches from the upper end. These distances are, however, of no particular significance, and may be varied as convenient. With these dimensions, and bobs weighing about three pounds each, the pendulum traverses its arc once in something less than 1.5 seconds. By placing the upper bob very low on its part of the rod, the time may be quickened to one second or under.[1]

The supporting-frame is made of wood seven-eighths of an inch thick, and has the following dimensions: base board 36 × 8 inches, uprights 24 × 4 inches, top board 34 × 6 inches.[2] The top board is pierced with an elliptical hole (8 × 2½ inches) as shown in Fig. *B*. The pendulum swings on the points of two screws passing through hardwood brackets fastened on opposite sides of the pendulum rod (Fig. *C*). These are 3⅛ inches long on the side next the pendulum rod, 2⅝ inches on that perpendicular to it, and ⅞ of an inch thick. The lower edge of the brackets is 25½ inches from the lower end of the pendulum.

The screws are ordinary steel wood-screws about 2¼ inches long, filed down to a sharp point at the lower end, and extending about an inch below the brackets. The points stand 2¼ inches outward from the pendulum rod on either side. It is important that these should go straight through the brackets, and that the line connecting their points should be perpendicular to the rod of the pendulum. The points rest in little sockets of brass and glass, as shown in section in Fig. *D*. The upper part is a strip of sheet brass, pierced with a conical hole about an eighth

1 The instrument may be given a very fine gradation of rates by having the upper bob so attached as to be moved up and down with a screw. For details of such an instrument, giving very slow rates, however, see Bowditch and Warren, The Knee-jerk and Its Physiological Modifications, *Journal of Physiology*, XI., 1890, 29 ff.

2 This frame was made in the first instance for another purpose, and some of its dimensions can be changed with advantage.

of an inch in diameter at the top and something over a thirty-second at the bottom. Between the brass strip and the top board of the frame (thus closing the bottom of this conical hole) is held a bit of smooth glass, a piece of a broken microscope slide, which furnishes the actual support for the screw-point mentioned above. These sockets must, of course, be so placed that they do not hinder the swinging of the pendulum, while they still keep it in its place.

On the back of the pendulum rod, a little below the point of support, a couple of binding-posts, such as are used for electrical connections, are fastened. The holes in these posts have been enlarged to about three-sixteenths of an inch. A bit of steel rod is passed through the holes, and on it a small brass weight is fastened, which can be shifted to one side or the other to compensate any inequality in the large weights, and make the rest-position of the rod come at the middle of the base-board.

The small tuning-fork (an ordinary one) is attached to the pendulum by thrusting its stem into a suitable hole near the lower end of the rod. The fork must be so placed that the tines vibrate lengthwise of the pendulum, not crosswise of it.

A *Rubber Hammer* is easily made by mounting a large rubber cork on a wooden handle.

Apparatus for Highest Audible Tones.—Simple apparatus for this purpose is all more or less unsatisfactory. The most convenient instrument is probably the Galton whistle, which can be had in different forms and at various prices, from about five dollars upward.[1] The instrument is a minute whistle or organ-pipe, blown by pressure upon a rubber bulb, and capable of change of length by means of a plunger which closes the other end of the tube. The

[1] Galton, Inquiries into Human Faculty, London, 1883, p. 375 ff.

precise tone given with any position of the plunger is difficult to fix, however, and varies with the pressure of the air with which the whistle is blown, so that tests with it, at the best, are very rough. All that the instrument can safely show, except when handled with elaborate precautions, is the general character of very high tones, and the fact that some persons can still hear tones that others cannot. The instruments also differ among themselves, and some are said to produce a good tone with settings at which others give one much obscured by the rushing sound of the air.

The following table of values is given by the Cambridge Scientific Instrument Company of Cambridge, England, from calculations based on experiments, for an instrument of very small bore (about 0.7 mm.) made by them; but it is hardly likely that they themselves would contend for a high degree of certainty in the values given, especially at the upper end of the scale.

LENGTH OF THE WHISTLE IN MM.	NUMBER OF VIBRATIONS.	LENGTH OF THE WHISTLE IN MM.	NUMBER OF VIBRATIONS.
1.0	42,500	3.0	21,250
1.2	38,600	3.5	18,890
1.4	35,400	4.0	17,000
1.5	34,000	5.0	14,170
1.6	32,700	6.0	12,140
1.8	30,360	7.0	10,630
2.0	28,330	8.0	9,440
2.5	24,290	9.0	8,500
		10.0	7,720

The following values are from results found by Stumpf and Meyer[1] in actual tests with a Galton whistle of a form

[1] Schwingungszahlbestimmungen bie sehr hohen Tönen, *Wiedemann's Annalen*, LXI., 1897, 760–779.

devised by Professor Edelmann of Munich. The bore of this instrument was 4 mm., and it was blown with compressed air.

NUMBER OF VIBRATIONS.	LENGTH OF THE WHISTLE IN MM.	NUMBER OF VIBRATIONS.	LENGTH OF THE WHISTLE IN MM.
4,000	19.6	10,000	6.6
5,000	15.2	11,000	5.7
6,000	12.4	12,000	4.8
7,000	10.4	13,000	4.25
8,000	8.85	13,600	3.9
9,000	7.5	14,000	3.7

The steel cylinders, sometimes used for demonstrating tones of very high pitch, are to be had from dealers in physical instruments generally; but of the accuracy with which they may give the pitches assigned to them, the writer is ignorant.

Apparatus for the Lower Limit of Pitch is also somewhat unsatisfactory. A good instrument for demonstration is said to be Appunn's lamella,[1] – a weighted tongue of steel giving rates from 4 to 24 per second. A thin strip of steel, loaded at one end and clamped in a vise, could perhaps be used, and its rate determined afterward by making it trace on a smoked glass plate or otherwise. In any case the tones thus produced are very weak, but will serve in Ex. 68, where the intention is rather the demonstration of the character of these very low tones than an exact determination of the limit of audibility.

Tuning-forks. — The tuning-forks needed for the experiments of this chapter are a set of large forks on resonance boxes, including the following: c, c' (two of this pitch), c''; a set of mistuned forks for just observable

[1] Anton Appunn, Nürnbergerstrasse, 12, Hanau a. M., Germany.

difference in pitch (or a pair of forks one of which is provided with running weights); ordinary forks giving a' and c'', and one giving c'''. It would also be convenient to have a set of large forks on resonance boxes, giving all the tones of the octave from c' to c'', but this is not necessary.

The *Large Forks on Resonance Boxes* will probably be purchased. The others can be made without very great trouble from the forks sold in the music-stores.

The *Set of Mistuned Forks* for just observable difference in pitch may be prepared from such forks. Select half a dozen forks, picking out those with prongs as nearly alike as possible in all respects, and such as sustain their tone well. Take one of these as a standard, and tune the next sharp by about one beat per second, the next by two, the next by three, and so on. The forks are tuned sharp by filing at the ends of the prongs, either so as to shorten them, or on the inside near the ends so as to make the ends lighter. Care should be taken to keep the prongs equal if they are so at the start, or to correct them if unequal. If too much is taken off, so that the pitch of the fork needs to be reduced again, file in the crotch of the fork, or on the prongs near the crotch, preferably the former. Having tuned the forks as near as convenient to the pitches required, mark them in some way so that they can again be recognized, and lay them aside for more exact counting later. For this later counting prepare a resonance bottle (see below), and holding both forks over it at once, count the beats for ten seconds if possible, counting the first beat "nought." Repeat the counting several times, but not at the same sitting, and take the average of the results. Beats from 2 to 4 per second are best for counting, and forks beating faster or slower than this can be determined indirectly, and the rates of all checked by counts of various

combinations.[1] The little riders mentioned in Ex. 71 may be made by cutting off quarter-inch bits from rubber tubing that will fit tight upon the prongs of the fork, or by using little spring clips of wire.

Forks giving a'' and c''', an octave higher than the ordinary a' and c'' forks, can be made by cutting off the latter, and tuning by beats with other a' and c'' forks. Fork a'', for example, will beat with a', and the tuning is to be continued till the beating disappears. The stems of the forks may in this case be pressed against a table top or sounding-board, to strengthen the partial tones on which the beating in large part depends.

For the *Resonance Bottle* mentioned above, any bottle may be used, and can be tuned to the right pitch by pouring in water, which raises the pitch; or, if the mouth is wide, by partially covering it with a card, which lowers the pitch. A six-ounce wide-mouthed bottle is about right for the c'' forks, and can be tuned for the a''s by partially covering the mouth with a card, the proper amount of covering being found by trial. When the amount is once found, the card may be fastened in position with wax. For picture and description of such bottles, see Mayer, "Sound," pp. 102 f.

The *Sonometer* is simply a long flat box with a very thin top, which serves as a sounding-board for the strings that are stretched over it. One can be had from the physical instrument-makers at prices from about five dollars

[1] The following are the directions for very exact counting given by Ellis, Helmholtz's Sensations of Tone, 2d ed., London, 1885, p. 443 f.: "Count on one day the beats between forks 1 and 2, 3 and 4, 5 and 6, etc., so that the same fork is not used for two counts on the same day. Excite by striking with a soft ball of fine flannel wound round the end of a piece of whalebone, as a bow is not convenient unless the forks are tightly fixed. Each blow or bowing heats, and hence flattens, and this tells if the experiments on any one fork are long continued. Count each set of beats for 40 seconds if possible, and many times over, registering the temperature and the beats, and taking the mean."

upward, or can be made by a carpenter. For dimensions and directions for making, see Mayer, "Sound," pp. 129 f. For many experiments any stringed instrument, of which many cheap forms are to be found in the music-stores, would do, or even a brass wire stretched across a table top.

The *Resonators* will probably be purchased. The best are spherical. Those made by König, the celebrated acoustical instrument-maker of Paris, may be had of the physical instrument dealers, but are expensive. Cheaper conical resonators are made by Appunn, but with these the writer has had no experience. For more refined apparatus for many of the experiments of this chapter, the catalogues of these makers should be consulted.

The *Piston Whistles* mentioned in the text could, a few years ago, be purchased in the toy-stores, but probably are not now in the market. Substitutes for them can easily be made, however, by notching a piece of small brass tubing of smooth bore exactly as a willow twig is notched in making a whistle, and fitting it with a bit of steel rod as a plunger. The mouth end of the whistle should not be cut slanting, as in a willow whistle, but left square. A three- or four-inch piece of rubber tubing may then be drawn over this end for a mouthpiece. Two such piston whistles may take the place of the bottle whistles.

The *Bottle Whistles* are even simpler in manufacture

than the piston whistles. They are made by fastening a piece of rubber tubing to the lip and neck of a bottle, as in the cut, or better still, by splitting the tube a little way so that the upper half may extend an eighth or three-sixteenths of an inch over the lip; but care must be taken that it does not project too far. Bottles of wide lip give good results. For a similar but more permanent construction, see Helmholtz's "Sensations of Tone," p. 60. For use in these experiments, prescription vials of ounce size will be convenient.

On *Apparatus for Making Hydrogen* consult a work on chemistry. Some means of mixing the hydrogen with air, and a glass tube for blowing the bubbles, will also be necessary. If bubbles can be blown of mixed oxygen and hydrogen instead of hydrogen and air, the effect will probably be more striking.

The "*Snapper Sounder*," or "telegraph snapper," is to be had of dealers in telegraphic supplies at from about thirty to seventy-five cents. That shown in the margin is of the lower priced sort.

In a number of cases experiments have been given for the piano or parlor organ. It is assumed, of course, that these will be borrowed. Sometimes the specially tuned *Harmonical*, designed by Ellis to illustrate the theories of Helmholtz (see description of the instrument in his translation of Helmholtz's "Sensations of Tone," pp. 466–469, also 17, 22, and 168), would be better. This instrument is made by Messrs. Moore and Moore, 104–105 Bishopsgate Street Within, London, E. C., at between forty and fifty dollars. For the proper tuning of the instrument, however, a special set of nineteen forks is necessary.

Apparatus for Chapters V., VI., and VII., on Vision, Experiments 104–233.

Of general apparatus the following will be required: a candle; two pasteboard tubes about an inch and a half in diameter and a foot long; a bit of straight wire six or eight inches long; three flat buttons; any convenient set of pictures (a set cut from the illustrated magazines and mounted on cards will answer every purpose); pieces of plain and colored glass, about 5 × 8 inches in size — two or three pieces of plain, one piece red, one piece green, three pieces blue, one piece each of any other convenient colors; white tissue paper, colored and gray papers, black and white cardboard; kindergarten materials (weaving strips, rings, and dots); and colored gelatine in the principal colors (including violet and purple), which may be substituted in many cases for the colored glass.

Colored and gray papers can be had from firms dealing in materials for color-teaching in the schools. A long series of gray papers, particularly full in very dark grays, is furnished by Rudolph Rothe of Prag. The black cardboard should be dull finished, not shiny. Colored cardboard is also to be had from the printers and stationers, and is very convenient in making diagrams requiring colored backgrounds. The colored gelatine can be had of some of the dealers in physical instruments or of those who furnish stereopticon supplies.

Of materials for special experiments the following will be required: a pink-eyed rabbit, with conveniences for etherizing and removing eyes, and a little modeling-clay; three or four inches of small platinum wire; a little chrome-alum, though this may be omitted if purple or violet gelatine is at hand. If the chrome alum is to be used, make a saturated solution in water, filter, and put into a flat-sided,

clear glass bottle. Dilute, if necessary, till the yellow spot can be observed as described in the experiment.

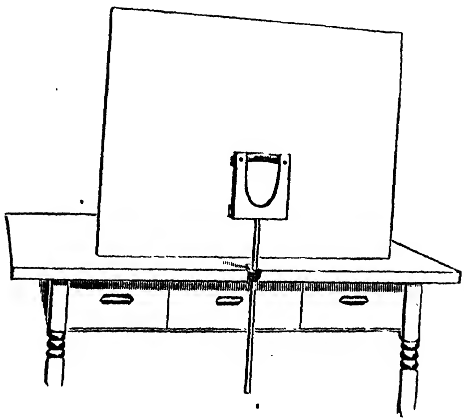
Of special apparatus there will be needed: a double convex lens of short focus (a reading-glass will answer); a double concave lens, e.g., a spectacle lens; an ordinary glass prism of 60° angle; a prism of 10–20° angle, to be had of dealers in oculists' supplies; a campimeter; a battery and electrodes for optical stimulation; an induction coil and small Geissler tube; a dark box with photographic shutter (the latter serves very conveniently in many cases as a substitute for the induction coil and Geissler tube); a color-wheel and a number of special disks; Holmgren's wools; a spectroscope; a metronome; a reflection color-mixer; a double refraction prism; a binocular color-mixer; a Galton bar; a krypteon; medallions and specially colored masks; a frame of parallel threads as described in Ex. 196 *c*; a concave mirror; an ordinary stereoscope (not very necessary); a haploscope; Martius-Matzdorff's set of diagrams; a Wheatstone stereoscope, convertible to a telestereoscope; a pseudoscope; a zöetrope; and a number of special diagrams for the experiment of the "fluttering heart."

The lenses, prisms, and several other pieces will, of course, be purchased, and need no further comment.

The *Campimeter* is simply a large but thin wooden plane with some sort of support for the head fixed before it. That in the Clark laboratory, which is shown in the cut below, has a surface of 3 × 4 feet, and is half an inch thick; a plane 2 × 4 feet would, however, answer every purpose.

The plane should be so made that it can be clamped to the table top. The head-rest is 8 × 9½ inches in size, strengthened by a two-inch piece across the back at the bottom, and mounted on the top of a steel rod, which is

clamped to the table edge with one of White's universal clamps (see section on General Apparatus). A simpler head-rest on the same principle can easily be made by substituting a fixed wooden upright for the adjustable steel



rod. The first form of head-rest is not absolutely rigid, but serves well enough for most purposes. If absolute rigidity is required, it is necessary to use a mouth-board like those described by Helmholtz and others.[1]

A more perfect, but also much more expensive, instrument for many of the purposes of the campimeter is the *perimeter*, which is to be found in many forms in the catalogues of the dealers in oculists' instruments.

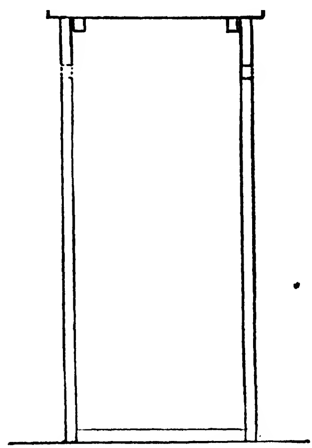
Electrodes for Visual Stimulation can be made by soldering connecting wires to plates of brass or zinc, two and

[1] For pictures of mouth-boards, see Hering in Hermann's Handbuch der Physiologie, III., i., pp. 440, 473, and 478: Helmholtz, Physiologische Optik 2te Aufl., p. 657 (p. 517 of the first edition); and Aubert, Physiologische Optik, p. 647.

a half inches wide by three long, and covering them with cloth. Some kind of a key for opening and closing the circuit, and a commutator for changing the direction of the current, are helpful, though not essential. For suggestions on batteries, see the remarks on General Apparatus.

A *Dark Box* of very simple construction is shown in section in the cut in the margin.[1]

A box seven inches square (inside measurement) and eighteen inches high, made of half-inch stuff, is convenient. The joints may be made light proof by covering with black cardboard or otherwise, and the box provided with a removable cover, with strips inside to keep it in place and prevent light from entering between it and the top of the box.



A little larger measurement than seven inches would be better, but that size has the advantage of being just right for the use of cardboard in lining the box. The ordinary black and white cardboards come 22 × 28 inches in size, and a complete lining of either black or white, can easily be made by cutting a strip of cardboard of the required color 18 inches wide, marking it off into four transverse strips, each 18 × 7, by cutting half through the card from the back with the point of a knife, and folding it up into shape. When an object or diagram placed within

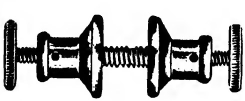
[1] Made after the scheme of Helmholtz; see his Physiologische Optik, 2te Aufl., p. 710 (p. 567 of the first edition).

the box is to be seen by instantaneous illumination, as in Exs. 200 and 218 *c*, it is well to line the box throughout with white. When very complete darkness is aimed at, as in Exs. 136, 178, and 226 *b*, the black lining should of course be substituted. The height of the box is unessential, 18 inches being taken smiply because it brings the top of the box, when standing on the table, a little above the eyes of a seated observer.

Opposite each other, in the front and back of the box, two horizontal slots should be cut, about 3½ inches long by half an inch wide; the first as an eye-hole, the second to allow a little light to enter through pin-holes in the diagrams when points of fixation are required. Round holes, suitably spaced, may take the place of the slots, and have the advantage of being easily stopped with corks if desired.

When some of the experiments of the course were written, a more elaborate box was in mind. Everything essential, however, can be done with the one described, and the slight changes in the setting of the experiments will offer no difficulty.

Instantaneous illumination can be secured by hanging a Geissler tube in the box, and discharging single induction sparks through it. A convenient way of introducing the current and hanging the tube is by means of double binding-posts having a head within the box and another without.



These can easily be made of a couple of binding-posts of the sort having separate screws for attachment, by sawing off the head of the screw, passing its stem through the side of the box, and screwing on another post inside.

Any induction coil that can be arranged to give single sparks can be used with the Geissler tube; but for general

laboratory purposes, apart from these experiments, the coil should be one in which the primary and secondary coils are separable, as in the Du Bois-Reymond sliding induction coil, well known in the physiological laboratories.

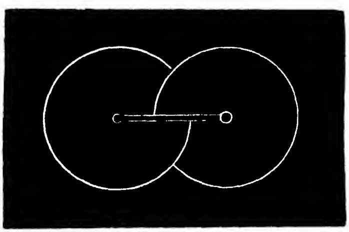
A better means of instantaneous illumination, in some ways, is a photographic shutter attached to the top or side of the box. It is a little difficult to cause the light from the shutter to fall on the diagram, but it may be accomplished more or less completely by properly adjusting the box with reference to the source of illumination, or by placing a mirror inside the box to direct the light upon the diagram.

The *Color-Mixer* or *Color-Wheel* is to be had in many forms from the different makers, at prices ranging from five dollars upward. In selecting an instrument, it is important to see that it is easily capable of sufficient speed to give a steady mixture with a disk composed of one part of black and one of white; that it runs so smoothly that the disk does not flutter; and that it is provided with means for ready determination of the proportions of the different colors combined, e.g., by a protractor, or by graduated disks. A little electric motor serves admirably in many cases, if batteries or other means of driving it are available. Many of the experiments can be made with the color tops sold as toys, or with the very simple one suggested by Dr. Bowditch in his "Hints on Teaching Physiology;" to wit, a button-mould fitted with a peg, and spun with the fingers. One an inch and three-quarters in diameter, and carrying disks two and a half inches in diameter, shows the contrast effects of Ex. 152 *d* as elegantly as could be desired. The disks are held in place by a piece of rubber tubing of very small bore, fitting snugly upon the stem, and twisted down upon the disks like a nut. A top of this kind with a large assortment of disks is now to be had from the physi-

cal instrument dealers at six cents each. An apparatus using larger disks, and operated on the principle of a boy's "buzzer," is contained in Bradley's Pseudoptical Set (as is also a little top like that just mentioned), but can only be used with disks in which the proportion of colors is permanently fixed; for the motion is alternately in opposite directions.

Several dealers furnish disks of colored paper in a variety of colors ready cut. These are a great convenience, and at times almost essential; for if the cutting is inexact, the disks will appear when in rotation with bothersome fringes of color.

When the speed of rotation is sufficient, disks may be slipped together, as in the cut below, and any required proportion of colors easily arranged. If the rotation is not sufficiently rapid, the sectors must be made smaller and more numerous. This is not much trouble when the proportions of color are to remain constant, but where adjustments are to be made, the multiplicity of sectors is a disadvantage.



Besides the colored paper disks, a number of special disks are required in the following experiments: —

Ex. 124*d*. (For this use the red saturation disk of Ex. 139.)

128*a*. Disk bearing a number of equal sectors of black and white; *b*, spiral disk (see cut on p. 117).

139. Set of saturation disks.

140. Disks for least change of intensity (see cut on p. 139).

141. Set of intensity disks (see cut on p. 141).

144. Disks for Fechner's colors (see cut on p. 395).

145. Disk with the same proportions of black and white, differently arranged in concentric rings (see cut, p. 144); also a disk with different proportions of black and white similarly arranged; this disk also shows contrasting grays (see cut, p. 145).

152. Contrast disk for grays (not necessary if the last disk above is at hand), also a set of disks for color contrasts (both pictured on p. 158).

160. Disk for retinal oscillation.

163*c*. Disk for contrast with induced color marked off by heavy lines of demarcation.

221*a*. Disk for stereoscopy with moving image (see cut p. 295).
  b. Disks for binocular stroboscopy (see cut p. 296).

223*b*. and 231. Disk with radial bands.

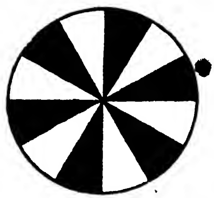
228*a*. Disks for monocular stroboscopy (see cut p. 296).

234*b*. Disks for demonstrating Weber's Law (see cuts pp. 335 f. and specifications p. 412 f.).

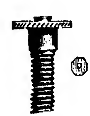
Where sets of disks are mentioned in the above list, single disks of a selected color may be substituted in case it is desired to limit the number. Most of the disks have been briefly described in the text, but a few additional particulars may be helpful.

In planning a full collection of disks, it is well to fix on a standard size that will be economical of cardboard. From board of the size before mentioned can be cut nine disks nearly eight inches in diameter, which is a convenient size for individual experimentation or demonstration before small groups of students. The same sheets allow the cutting of two disks of fifteen inches in diameter. When no size is specified, the 8-inch disks are meant; when large disks are mentioned, the 15-inch, unless special measurements are given. Most of the cuts in the text show the disks in the form required for moderate rates of rotation, and even when a high rate is attainable, it is convenient to have these permanent disks adjusted for slower rates, because of the steadier motion.

For the black-and-white disk of Ex. 128 *a*, that used in Ex. 152 *d*, or indeed almost any one of the black-and-white disks of other experiments, could probably be used. If a special disk is required, it may be made like that in the margin.



The spiral disk for Ex. 128 *b* should be of the larger size. It is interesting to vary the experiment by using two disks at the same time, one large and one small, carrying spirals of opposite direction, the small one put on in front of the other. To draw a spiral on the disk, it is only necessary to fasten a pencil in a thread as for drawing a circle, and then to have the thread wind about a post of suitable size as the pencil makes its circuits; or, better perhaps, to start with the thread wound up, and to trace the spiral as the thread unwinds. A little care and practice will produce satisfactory results. The writer has found it convenient in drawing spirals to fasten the cardboard upon a plank or table top, and to screw into the plank through the cardboard a screw-post, like that shown at half size in the margin. The post is slightly less than 0.3 inches in diameter under the head, and thus gives a spiral with the corresponding parts of the turns almost exactly an inch apart. The thread is put through a hole in the head of the post, then carried up and fastened out of the way about the little knob on top. In order to keep the pencil from getting away from the thread, a bit of sheet brass was bored with a sixteenth-inch hole, and tied at the end of the thread. This is shown at the right in the cut. A convenient width for the black line of the spiral is seven-sixteenths of an inch, and for the white, nine-sixteenths.

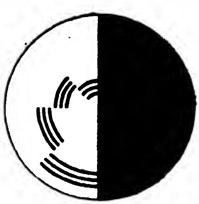


The saturation disks may be made in the six principal colors (red will be especially needed), and will be made most easily by pasting colored papers upon white disks. The color must be given a leaf shape, something like the black in disk *A* on p. 335, but narrower, and may, with advantage as regards speed, be distributed upon six radii instead of three.

The disk for least change of intensity in a white ground is sufficiently described in the text, p. 139.

The disks for showing simultaneously the whole range of intensities are made like the saturation disks; but the colored paper is this time given a star shape, as in the cut on p. 141, and is pasted upon black disks instead of white. While not required for the experiment, a black disk carrying a white star may well be added for the beauty of the grays which it presents.

Almost any of the black-and-white disks will show Fechner's colors when rotated at the proper speed. For the pierced disk mentioned, Rood made use of four radial



B

slits of 7° each; the disk should be of black cardboard. Since Ex. 144 was printed, interest in these colors has been aroused by the publication in *Nature* of a description of a special top that exhibits them (vol. li., 1894–95, see the index under "top"). Fig. *A* above shows the original form described. *B* is a form recommended by a later cor-

respondent in *Nature* (p. 510), but untried by the present writer. It has the advantage of making the proportions of black and white variable, which is said to be an important condition. A black disk and a white one carrying a spiral are combined, as indicated on p. 392 above. The spiral line in the cut is unfortunately much too wide — a line only one-fifth the width of the intervening white spaces, or even less, is recommended.

The disk with equal quantities of black and white, but differently distributed, and that for different proportions of black and white similarly distributed, will be sufficiently clear from the cuts on pp. 144 f. The latter is repeated, except as to the number of gradations, in a form for slower rotation, in the cut at the left on p. 158. Both would be improved as contrast disks by a margin of white on the outer edge.

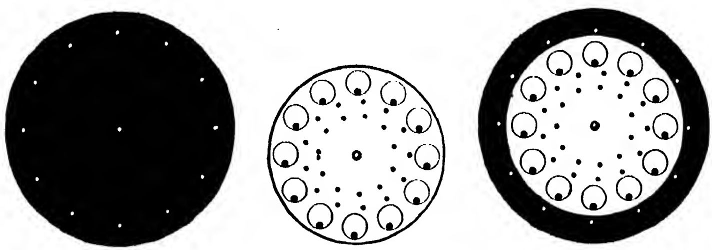
The disks for color contrast may be prepared in various colors, e.g., in the four principal colors, or if this seems more than necessary, in green alone (see cut at the right on p. 158). The color may be conveniently applied, as before, in the form of colored paper. A similar disk, carrying two narrower concentric rings for contrast, one bordered on both sides by a heavy black line (e.g., 1 mm. broad), is used in Ex. 153 *e*. Both will probably be fully understood from the description in the text (pp. 158 ff.).

The disk for retinal oscillation is also described in the text (p. 168). The dimensions there given are not essential; smaller disks serve as well. The same is true of that for stereoscopy with moving figures (pp. 294 f.). The only important point is that the smaller circle should not be too eccentric.

The disks for binocular stroboscopy (p. 296) as used in the Clark laboratory are unnecessarily large (*A* 22 inches, *B* 16$\frac{3}{8}$ inches, and *C* 13 inches). For most purposes the

following dimensions would be better: *A* 15 inches, *B* 11 inches, *C* $7\frac{1}{2}$ inches. If the latter are chosen, the following would be about right for the dimensions of the slits: narrow slits in *A* $1\frac{1}{4}$ inches long, with their outer ends $\frac{1}{4}$ inch from the edge of the disk, breadth 6°; the curved sides of the broader openings 5 inches and $3\frac{3}{4}$ inches respectively from the centre, angular breadth about 40°. The slits in *B* should be the same distance from the centre as the larger openings in *A*, and in angular extent the same as the narrow ones, that is, 6°.

Disks for showing the ordinary phenomena of stroboscopy with the color-wheel and a mirror may be readily pre-



A B C

pared in the laboratory. The size of the disks will of course vary with the apparatus with which they are to be used; the following dimensions are from a small stroboscope turned by hand, but can easily be changed to make disks suitable for the color-mixer.

Diameter of disk *A* $7\frac{7}{8}$ inches, diameter of circle on which the openings stand $6\frac{1}{2}$ inches, diameter of openings $\frac{3}{16}$ inch. These openings were cut with a belt punch; they may be replaced by radial slits if more convenient. Diameter of disk *B* $6\frac{1}{8}$ inches, diameter of circle passing through the centres of outline circles $4\frac{7}{8}$ inches, diameter

of circle passing through the centres of outer ring of black dots $3\frac{9}{16}$ inches; same for inner ring of black dots $2\frac{5}{8}$ inches. The outline circles are just under $\frac{7}{8}$ of an inch in diameter, and the solid black dots inside them just under $\frac{1}{4}$ of an inch. *C* represents the disks combined for use. Unless both sides of the large disk are black, it will be found better, however, to turn *A* over so as to bring the black side next the eye. Such a pair of disks shows all the essential phenomena of the stroboscope.

The disk with radial bands like spokes, mentioned in Exs. 223 *b* and 231, should be of the larger size (15 inches), and may carry a dozen bands each half an inch wide.

Colored worsteds for making Holmgren's test for color-blindness can be had from the dealers in oculists' apparatus, either in little separate skeins, or arranged in more or less elaborate fashion in frames or holders of some sort. A simple set is to be found in the front of Galton's "Life History Album."

The *Spectroscope* used in the Clark laboratory for Exs. 138 and 141 *b* is a single prism instrument of no very great expense. Any instrument which shows the Fraunhofer lines as far as *H* without too much difficulty would probably answer.

The *Metronome* in Ex. 145 is such as is used by musicians. If the pendulum mentioned above (p. 377) were arranged with an electrical contact and made to work a telegraph sounder, it would answer equally well for this purpose and would be otherwise useful. The simplest sort of electrical contact is made by carrying a fine wire down the pendulum rod, and allowing it to dip into a little globule of mercury in a mercury cup on the base-board. The upper end of the wire twisted into an open spiral may be fastened to a binding-post set into the front of the frame near the point of support of the pendulum, and will not in-

terfere very much with the swinging. A convenient mercury cup may be made by fastening a short bit of glass tubing with wax upon the top of the upper screw of a double binding-post. Such a cup is adjustable in height, and has in the lower binding-screw a means of connection with the rest of the circuit; but care must be taken to remove the lacquer from the top of the upper screw so as to insure good contact between the brass and the mercury.

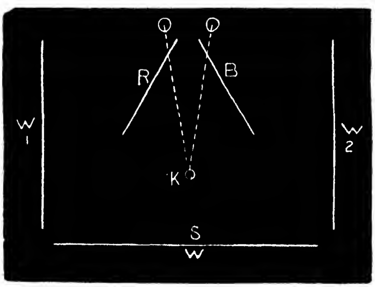
The construction of the *Reflection Color-Mixer* is probably sufficiently clear from the description and cut on p. 150. The same is true of the *Apparatus for Ragona Scinà's Experiment* (p. 156). This experiment does not, however, require a special piece of apparatus, the effect being very clear when the diagrams are in the same plane and the colored glass is held vertical like the plain glass in the reflection color-mixer.

For the *Double Refracting Prism* in Ex. 150 *b* use a crystal of Iceland spar, to be had at a small price from the physical instrument dealers. The requirement of achromatism made in the last line of the experiment is unnecessary.[1]

The *Binocular Color-Mixer* mentioned in Exs. 156 *a* and 167 *a* is a piece of apparatus devised by Hering, and described by him in the *Zeitschrift für Psychologie*, I., 1890, 23–28. It is made by Rothe of Prag, in neat form and at a low price; but the apparatus is simple, and any carpenter can make of wood one that will answer. The aim in Ex. 156 is to secure a binocular mixture of blue and red. For this purpose blue and red glasses may be used before the eyes, provided that a good deal of white can also be mixed in with the color of the glass. This is accomplished by letting the glasses stand at an angle, and reflect on their

[1] Rothe makes a simultaneous contrast apparatus after a plan of Hering's, in which such prisms are used. The instrument is convenient for demonstrating color-mixing by this method as well as for contrast.

upper surface the images of suitably placed white screens. The quantity of white light is regulated by the position of the screens with reference to the source of illumination, and by the inclination of the colored glasses. The following cut shows the arrangement of glasses and screens. W_1 and W_2 are the screens, R and B the red and blue glasses, W a white surface. In the carpenter-made instrument in the Clark laboratory the following plan and dimensions were used: in the middle of a base-board, 30 inches long and 12 inches wide, was placed another board 12 inches long and 10 inches wide, leaving a margin of an inch on each side, and of 9 inches at the ends. This little platform bears a piece of white cardboard corresponding to W in the diagram. On the nearer edge of this platform is fastened an upright piece 15 inches high and 3 inches wide. At its upper end, on the forward side, this upright carries the frames that hold the glasses R and B. The glasses are 4 inches square, and are framed on three sides only, the upper edge being left free so that the glasses may come close to the eyes. (Glasses 2 inches square, or even less, would do as well or better.) The frames are small pieces of board 6 inches long and 5 inches wide, with a square piece (three and three-quarter inches on the side) taken from the middle of their upper ends, leaving each like a U with very square corners and a heavy bottom. Over these square holes the glasses are fastened. The frames are fastened with a single screw each to the upright before mentioned,



the screws entering the frames about an inch and a half below the free edge of the glass. When in position, the glasses rise about three-quarters of an inch above the top of the post, and stand like the sides of a roof. They do not quite meet, however, but leave a space for the observer's nose between them when the apparatus is in use. The screws that hold the frames should be tight enough to keep them in position, but not so tight as to prevent their turning in adjustment.

The side screens of the instrument are exactly alike, and the description of one will do for both. Each is a piece of half-inch board 9 inches wide and 13½ inches long. This board turns midway from top to bottom on two screws put through the sides of a light frame just large enough to enclose it. The frame itself is fastened to a broad piece of board, which forms its base and rests in turn on the base-board of the instrument. A peg in the middle of the base of the frame, fitting into a hole in the base of the instrument, allows the rotation of the frame and screen about a vertical axis. The screen is thus made adjustable in two directions. Its face is covered with white cardboard. It is highly important that all the white surfaces be without noticeable spots, and the colored glasses free from flaws.

The instrument in this condition will serve for binocular color-mixing. For simultaneous contrast by Hering's binocular method (Ex. 156) some slight additions are required. On the front of the upright, and six inches upward from its foot, a wire about three and a half inches long is set, and extends forward perpendicular to its surface. At the end of the wire is a little button of cork, the fixation point *K* in the diagram. On the surface *W*, and parallel to this wire, is pasted a strip of black paper, a quarter of an inch wide, represented by *S* in the diagram.

An instrument constructed on this plan is unnecessarily

cumbrous, and would probably work as well if the side screens as well as the glasses were somewhat reduced in size. The rotation of the screens about a horizontal axis is also hardly worth while.

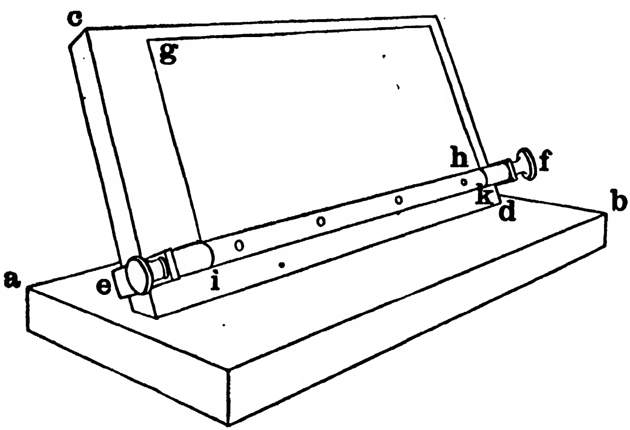
The *Frame of Parallel Threads*, mentioned in Exs. 196 *c* and 210 *c*, is probably sufficiently clear from the text.

The *Galton Bar* can be had ready made of the Cambridge Scientific Instrument Company, under the name of "Line Division Testing Apparatus." As furnished by this company it consists of an ebonite strip 10 inches long, 1 inch wide, and an eighth of an inch thick. On the back of this, and extending over a little from either edge upon its face, is a light brass slide. The parts that extend over upon the face carry between them, crosswise of the bar and close to its surface, a white thread which divides the bar into two portions, equal or unequal, according to the setting of the slide. On the back of the bar is a fine cross-line marking the middle of the bar. This line is visible through a rectangular opening in the back of the slide, and on the edge of this opening a scale is cut, divided to tenths of an inch, by which the position of the slide, and so of the above-mentioned white thread, can be read at any instant in tenths of an inch, or, since the bar is 10 inches long, in percentage of the total length. Besides the middle line there are also lines at one-third and one-fourth the length of the bar, so that estimates of these fractions can also be made. It would be easy of course to make such a bar from any rule that is divided on one side only, or even from a straight wooden slat on which a strip of millimeter paper has been pasted.[1] For a somewhat different form of the Galton bar, see the apparatus for Chap. VIII., below.

[1] It should be noted, however, that the ordinary metric cross-section paper does not measure true both ways.

The instrument, which for brevity I have ventured to call a *Krypteon*, is very simple in principle, — nothing more, indeed, than a slanting board with a flap hinged at the bottom of it. It is roughly pictured in the accompanying cut.

On a base-board *ab*, 8 × 20 inches in size, is set the board *cd*, 6 × 18 inches, inclined backward about 30° from the vertical. At the ends of this board near the base are fastened short brass arms, which extend forward and sup-



port the rod *ef*. They are of such length as to bring the centre line of the rod $\frac{5}{8}$ of an inch from the board *cd*, and $\frac{7}{8}$ from *ab*. The rod *ef* is provided with milled heads at the ends, so that it may be rotated easily with either hand. The rod itself is composite, being made of pieces of half-inch half-round brass, put together flat side to flat side, to make a single round rod. The forward half of the rod is in three pieces. The middle piece *ik* is held in place by screws, and can be removed; the end pieces are soldered

fast to the back half of the rod. This arrangement makes it possible to clamp securely into the rod the cardboard flap *gh*, or to interchange flaps if for any reason this is desired. When the flap is in position, the turning of the rod *ef* will rapidly cover or uncover anything placed on the inclined surface *cd*. In using the krypteon in Ex. 174, a narrow strip of wood should be tacked along the inclined surface to support the Galton bar. The instrument is not limited in its usefulness to this single experiment, but can be used for experiments with after-images and successive contrast, and for any others in which a sudden revealing or hiding of an object is desired. The instrument can hardly be regarded as a necessity, however, and a simple substitute can readily be found for it.

The *Concave Mirror* used in Ex. 183 *b* is to be had of any optician or physical instrument dealer at small cost.

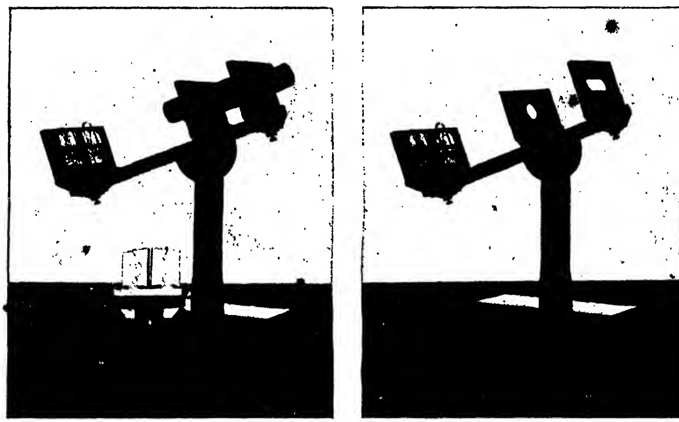
The *Mask* in Ex. 184 can be purchased at a toy-store, and colored as required. It is convenient to have two masks so that the external and internal aspects may be presented simultaneously — in this case, of course, only one need be colored. It is well also if both can be mounted in some way for more ready handling. Medallions in plaster, about four inches in diameter, may be had in many art stores at a very low price, and casts of these in opposite relief may be taken in the laboratory by oiling the surface carefully, surrounding the edge with a strip of paper, and pouring on plaster of Paris mixed to about the consistency of cream.

An *Ordinary Stereoscope* is convenient for beginners in binocular experiments, but is hardly necessary, especially if a haploscope or Wheatstone stereoscope is included in the collection.

The *Haploscope* is nothing but a simplified stereoscope, and has the sole purpose of presenting to each eye a field

invisible to the other.[1] It is hardly necessary if a Wheatstone stereoscope is at hand. In the cuts below is shown a somewhat elaborate form of it.

In the figure at the left the instrument is arranged for parallel vision, in that at the right for crossed vision. In the left figure, leaning against the base, are also shown the special movable diagram-holders for Le Conte Stevens's Experiment (Ex. 221 *e*). It would probably be equally convenient and much less expensive to purchase two ordinary



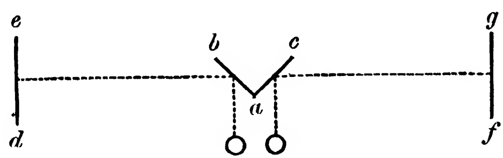
stereoscopes, remove the lenses, and reconstruct one into a haploscope for parallel vision and the other into one for crossed vision, than to make one after this model. For this reason specifications are omitted, but a few measurements will give a more definite idea of its size: base-board, $12\frac{1}{2} \times 5 \times 1\frac{5}{8}$ inches; height of central standard to centre of axis of the inclined bar, $10\frac{3}{4}$ inches; inclined bar,

[1] The term *haploscope* is used by Hering for a piece of apparatus much more like the Wheatstone stereoscope.

18 × 2 × $1\frac{3}{8}$ inches; eye tubes, $9\frac{1}{4}$ inches long, $1\frac{1}{2}$ inch (inside) diameter, centres of tubes $2\frac{1}{2}$ inches apart.

The best *Stereoscopic Diagrams* with which the writer is familiar are those referred to in the text as Martius-Matzdorff's diagrams. The set consists of 36 diagrams and an explanatory pamphlet, and is published by Winckelmann und Söhne, Berlin, under the title, *Die interessantesten Erscheinungen der Stereoscopie.*

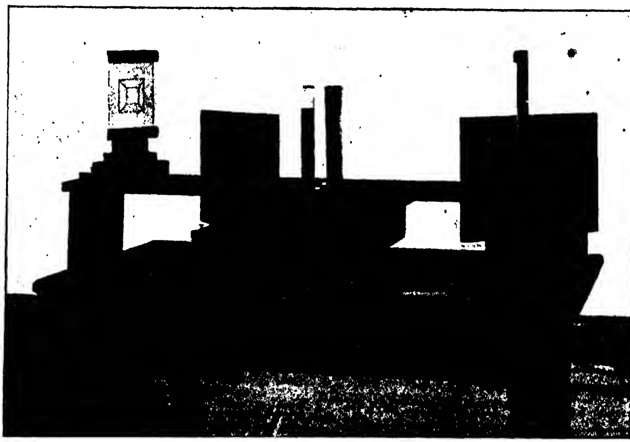
The *Wheatstone stereoscope* is very simple in plan, as may be seen from the cut below.



The eyes look into mirrors set at right angles to each other, *ab* and *ac*, and see the reflected images of diagrams placed at *de* and *fg*. In actual construction, however, the instrument is varied somewhat from this very simple plan. Thus for experiments with diagrams at different distances, it is desirable to have *de* and *fg* movable to and from the mirrors; for experiments with different degrees of convergence, to have the mirrors and diagrams movable together about centres lying below the mirrors (or better still about centres lying in the same vertical lines as the centres of rotation of the eyes); for use as a telestereoscope the diagram-holders *de* and *fg* must be replaced by large mirrors parallel to the small ones (see plan on p. 279); and if Stevens's experiment is included, the diagram-holders must be turnable about a vertical axis.

The following cut represents a large wooden apparatus

built up, a little at a time, in the Clark laboratory. The base of the instrument is a bench 8 inches high, 12 inches wide, and 4 feet long. On this rest arms which carry at their inner ends little columns, at the upper ends of which are attached the mirrors corresponding to *ab* and *ac* of the plan, and at their outer ends the diagram-holders, the left one of which is turned part way so as to show the diagram



in place. Back of the bench stand the large mirrors which take the place of the diagram-holders when the instrument is used as a telestereoscope. Underneath the bench is hung a drawer in which the diagrams are kept when not in use.

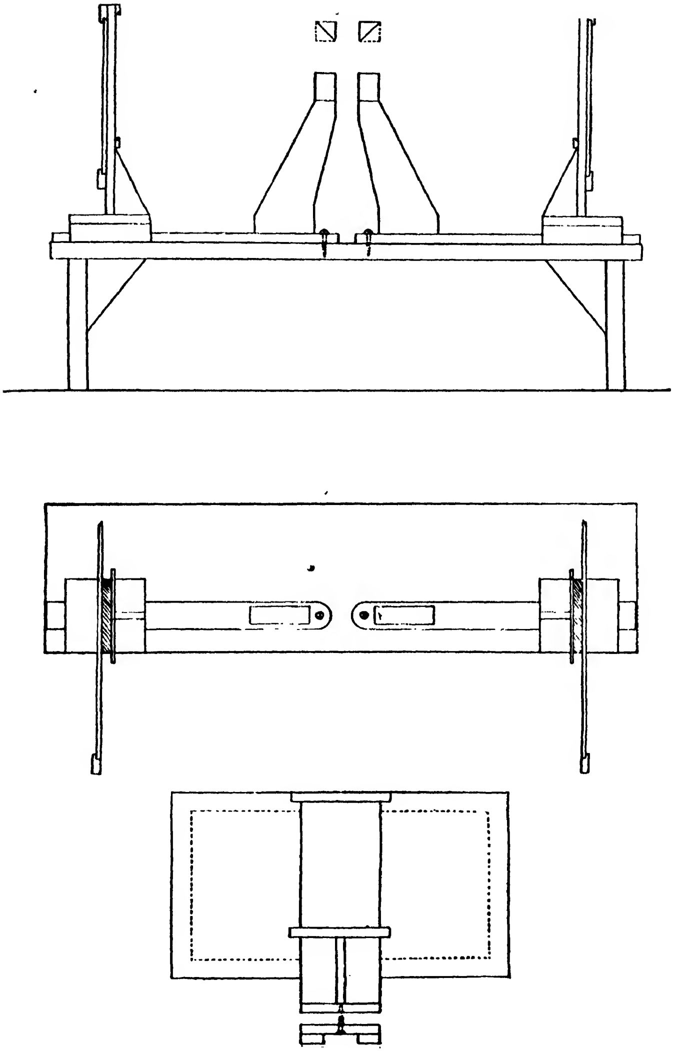
For the experiments of this course, however, a somewhat smaller and simpler apparatus would be not only more convenient, but in many ways better; and the writer therefore offers the following plans instead of a detailed de-

scription of this instrument, though circumstances have forbidden their execution at the time of writing.[1]

The plan shows the instrument on a scale of about one-tenth. The first figure shows the front view; the second, the horizontal plan; and the third, one of the diagram-holders seen from the station of the mirrors.

The base of the instrument is to be a wooden bench 30 inches long, 8 inches wide, and the same in height. On the top of this bench are fastened two arms made of narrow strips of hard wood 14½ inches long, 1½ inch wide, and half an inch thick, as shown in the first and second figures of the plan. The adjacent ends of these arms are rounded, and they are fastened to the top of the bench with a single screw each. These screws serve as pivots about which the arms can be turned. The separation of these screws should be 2¼ inches from centre to centre, and they should be set two inches back from the front edge of the base-board. Each arm carries also near its inner end an angular bracket which supports the mirror. These brackets may be made an inch thick, and 8¾ inches in height from the upper surface of the arm. Their extent on the arm is not important, provided it is not too great, say 3 inches; and they should be cut back, as shown in the plan, enough to allow the insertion of the pivot screws. They must be so set that the centre line of the mirror surface stands exactly over the centre of the pivot screw. The uppermost inch and a half of these brackets is first worked out one inch square, and then cut away on the diagonal so as to receive the mirrors, somewhat as shown by the small figures just above the brackets in the first figure of the plan.

[1] For plan and description of a refined and somewhat specialized instrument of this kind, see Hillebrand, Die Stabilität der Raumwerthe auf der Netzhaut. *Zeitschrift für Psychologie*, V., 1893, p. 38; see also Hering, *Hermann's Handbuch der Physiologie*, III., i., 393 f.



The surface left for the mirrors is thus nearly an inch and a half square.

The mirror itself, one inch square, may be framed in cardboard, and attached by very small screws to this surface. A cardboard frame can be built up as follows: from pasteboard as thick as the mirror glass cut a piece $1\frac{1}{2}$ inch square, and cut in its centre an inch square hole to receive the mirror. Paste on the back of this a $1\frac{1}{2}$ inch square of thin cardboard, put the mirror into its place, and paste on in front of it a piece of black cardboard having a $\frac{7}{8}$ inch square cut in its centre.

The diagram-holders are of simple construction. Each consists of a sliding block four inches square and half an inch thick, on the bottom of which are fastened two cleats (each $4 \times 1\frac{1}{4}$ inches), leaving a space between them just equal to the width of the arm. On this sliding base rests another block of the same dimensions. The two are held together by a single screw put up from below through the middle, as indicated in the third figure of the plan, where the blocks are a little separated. The screw must fit tight enough in the lower block to allow the upper to be turned stiffly. On the middle of the upper block rises the upright of the diagram-holder ($11\frac{1}{2}$ inches high, 4 inches wide, and half an inch thick). Crosswise of this are fastened two little guides of wood for receiving the diagrams (which are themselves $5\frac{1}{2} \times 7$ inches in size). These should be placed as high as the upright will allow. The upright is braced by a little bracket in front, as shown in the plans. The mirrors required, when the instrument is to be used as a telestereoscope, should be of good quality and 8×15 inches in the clear. They should be framed in plain wooden strips, and the frames fastened to the backs of the upright pieces of the diagram-holders. In using the telestereoscope on the actual landscape, it is well to open

the windows so as to avoid the distorting effects of the ordinary window glass.

The *Pseudoscope* in the Clark laboratory is of the sort manufactured by Pellin of Paris. The instrument is convenient, but a less expensive one would answer every purpose. Two total reflection prisms placed at the proper distance apart on a block, and kept in place with wax, could probably be used. If a construction of more permanent character is undertaken, it should allow for some rotation of the prisms about their vertical axes, and for an alteration of their separation.

Diagrams for the Experiment of the "Fluttering Heart" (Ex. 230) are perhaps sufficiently described in the text; but the following details with regard to the set in the Clark laboratory may not come amiss, though they are not furnished as beyond improvement. The colored papers used were mostly those supplied by the Milton Bradley Company, and reference will accordingly be made to their standards throughout. For Ex. 230*a* blue rings on a red ground: blue, kindergarten rings of standard blue; red, about equal to orange-red. For red rings on a blue ground: red, Bradley's red kindergarten rings; blue, something between blue and violet-blue, but darker than either; cross lines, very narrow strips of white paper. For Ex. 230*b* gray figures on colored ground and colored figures on gray ground: gray on red, gray about equal to that given by 270° black cardboard combined with 90° white on the color-mixer; red about equal to orange-red. Colored figures on gray ground, rings of standard orange; gray, that used for the cover of the *American Journal of Psychology*. In the second paper of Szili, mentioned in the text in connection with this experiment, will be found specifications for diagrams made from the Helmholtz papers (furnished by Jung of Heidelberg) and commercial gray papers of

German manufacture. The same author uses grays shaded to the proper depth with a lead-pencil.

Apparatus for Chapter VIII., on Weber's Law and the Psychophysic Methods, Experiments 234–239.

The only pieces of apparatus requiring special mention in this case are the disks and set of weights used for demonstrating Weber's law, and the special form of Galton bar used in the experiments on the psychophysic methods.

The *disks for Weber's law* are described in the text, but the following details of the specimens in the Clark laboratory (see Figs. *C* and *D*, p. 336) may be helpful. The disks are 40 cm. in diameter (though 15-inch disks would answer just as well). Beginning at the centre, the black extends unbroken for a distance of 2.5 cm. At that point the white begins, and gradually increases till, at a point 16 cm. further out (1.5 cm. from the edge of the disk), it occupies the whole 360°. The black is distributed on three radii, as the cuts show; and the curves were plotted according to calculations made for the angular amount of white at each centimetre from the point at which the white begins to the point at which it occupies the whole circumference. Since the black is not absolutely black, but reflects a small amount of light, an allowance is made for this amount, on the assumption that the black is about one-fiftieth as bright as the white of the cardboard from which the disk is cut. The table on page 413 gives the angular extent of white at the indicated distances from the centre.

These particular disks are finished by a narrow black line all the way around at the extreme edge of the disk, but this is not at all essential.

Dr. Kirschmann gives general formulæ for such calculations in the article cited in the bibliography of Chap. VIII. For the brightness values of various black pigments in comparison with white paper, see an earlier article by the same author (*Wundt's Philos. Studien,* V., 1889, 300).

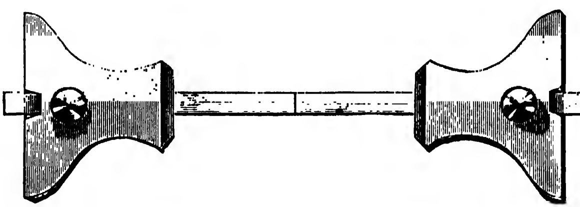
Angular Extent of White.

DISTANCE FROM THE CENTRE IN CM.	ARITHMETICAL SERIES, DISK *C.*	GEOMETRICAL SERIES, DISK *D.*	DISTANCE FROM THE CENTRE IN CM.	ARITHMETICAL SERIES, DISK *C.*	GEOMETRICAL SERIES, DISK *D.*
2.5	0.0°	0.0°	10.5	180.0	44.6
3.5	22.5	2.0	11.5	202.5	59.0
4.5	45.0	4.6	12.5	225.0	77.4
5.5	67.5	8.0	13.5	247.5	100.8
6.5	90.0	12.2	14.5	270.0	130.8
7.5	112.5	17.6	15.5	292.5	169.1
8.5	135.0	24.5	16.5	315.0	217.9
9.5	157.5	33.3	17.5	337.5	280.3
			18.5	360.0	360.0

The *Weighted Envelopes* used in Ex. 236 were made by loading stout manila "pay envelopes," $4\frac{1}{4} \times 2\frac{1}{2}$ inches in size, with pieces of sheet lead, or, in the case of lighter weights, with pieces of cardboard. A series was thus produced ranging from 5 to 100 grams. As originally planned, the series consisted of 106 weights, besides the light and heavy standards, which were duplicates of the lightest and heaviest weights of the series. The differences were not uniform throughout, but smaller with the smaller weights and larger with the larger: 5 to 10 grams, 26 weights, difference 0.2 gram; 10.5 to 25 grams, 30 weights, difference 0.5 gram; 26 to 50 grams, 25 weights, difference 1 gram; 52 to 100 grams, 25 weights, difference 2 grams. Some such arrangement of the differences is necessary if the heavier classes are not to be very much larger numerically

than the lighter. As actually used, the series consisted of 118 weights besides the standards, 104 from the regular series, and 14 others of weights between 36 and 38 grams. In all of the envelopes, even the lightest, a piece of thin cardboard (twice the size of the envelopes, but folded once) was placed to stiffen them, and make the light and heavy ones feel a little more alike. The envelopes should be lifted vertically between the thumb and finger; and the lead, when it does not fill the envelope, should lie at the lower end. For this particular experiment the weighing does not need to be extremely exact; a fair approximation to the values given above is sufficient.

The form of Galton bar used in Exs. 238 and 239 is shown at about half size in the following cut.



It consists of a narrow steel rule, graduated on the back in hundredths of an inch, and divided on the face by a single line in the middle, and of two large sliding-pieces, one at either end. The instrument was made of two of Messrs. Brown and Sharp's rule depth gauges. All the graduation was removed from one side of the rule, the single middle line put in its place, and the inner ends of the two heads, or sliding-pieces, bevelled down to the surface of the rule. Either head can be fixed firmly in place by means of the screw on its upper surface. The rule itself is, in this case, only six inches long, which is incon-

veniently short; but longer rules could probably be obtained from the makers. The chief advantage of an instrument of this general form (and more convenient variants are quite possible) is that it allows the setting of a constant standard extent with which the variable extent is compared, — a point of little consequence, perhaps, in investigation, but of some importance in the exposition of the psychophysic methods. In Exs. 238 and 239 standards were chosen that left little or none of the ends of the rule exposed beyond the heads.

General Apparatus.

Besides the apparatus for specific purposes already considered, a certain amount of general apparatus, used more or less in all experiments, is required. The needs of those making use of this chapter will probably differ so widely that the writer contents himself with enumerating what is likely to prove useful without advising as to style or quantity.[1]

First is to be mentioned a substantial set of rods, stands, clamps, and couplers. They may be had of any dealer in physical or chemical apparatus, but vary much in quality. Those should be selected which are well enough made to be firm and solid when combined for use. A combination that will wobble when set up is of no satisfaction whatever. A few universal couplers or ball-joint clamps are very convenient. A variety of ball-joint and swivel clamps and couplers manufactured by Otis C. White of Worcester, though not originally intended for laboratory use, have given eminent satisfaction, and may now be had from some of the physical instrument dealers. One of the ball-joint

[1] For other general suggestions on laboratory furnishing, see the writer's paper, "Some Practical Suggestions on the Equipment of a Psychological Laboratory," *American Journal of Psychology*, vol. v., 1892-93, 429-438.

table clamps with rod to fit has been presupposed in the description of the head-rest of the campimeter (p. 388). Besides these, a number of ordinary iron clamps, such as are to be had at the hardware stores, are useful for attaching pieces of apparatus to the table.

Electric batteries have several times been mentioned or implied in previous paragraphs. Ex. 121 has been made in the Clark laboratory with a battery of four Leclanché cells of the "gonda" pattern, but these are less convenient for other purposes. For running small electric motors, induction coils, and the like, the Edison-LaLande battery (type S for example) has been recommended, and would serve equally well for any of the experiments of this course, though it has not been used for them by the writer. These, however, are not convenient for taking from place to place. For the latter purpose, the familiar Grenet battery would be preferable.

A set of drawing-instruments is essential if disks and diagrams are to be prepared in the laboratory, and to that may be added india ink, brushes, etc. A few of the common carpenters' and machinists' tools are also almost indispensable.

Delicate balances for use in making the minimal weights of Ex. 22, and coarser ones for the cartridge weights for Exs. 24 and 34, have been assumed in the experiments above. If the weights are not bought ready made, and the scales cannot be borrowed, they must be added to the required apparatus. The same is true of measuring-vessels for making the solutions for the taste and smell experiments.

Additional Apparatus for Alternate Forms of Experiment.

In a few cases alternate forms of experiment have been mentioned which call for apparatus not included in the

lists considered. A few words about these pieces may be in place.

The *Antirrheoscope* mentioned in Ex. 128 *d* is the same described and pictured by Bowditch and Hall (*Journal of Physiology*, III., 1880–82, 297–307) and by James in his "Principles of Psychology," II., 245.

The *Apparatus of Dvořák* (Ex. 221 *b*) is described in his original paper (see Bibliography of Chap. VII.), and referred to more fully than in the text in the *American Journal of Psychology*, VI., 1893–95, 575 ff.

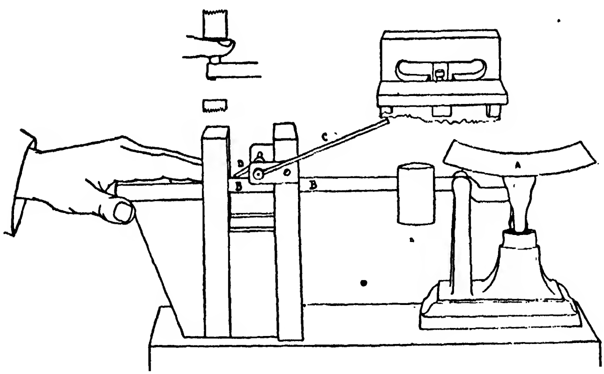
Some form of *Rotating Drum* has once or twice been mentioned, and the instrument has a wide usefulness in experiments not included in Part I. of this course. The best instruments of this kind (known from one of their physiological applications as Kymographs) are all very expensive. Cheaper substitutes are offered by various makers in this country and abroad, some for movement by hand, and others by clockwork or small motors. In selecting one, care should be taken to get a drum that runs true on its axis, and, if self-driven, as uniformly as possible.

The Pressure Balance, though mentioned in the experiments as an alternate only, is convenient, and may be briefly described. The one in the Clark laboratory, made after the suggestion of Professor Jastrow,[1] consists of a medium-sized Fairbanks' letter-scale provided with a wooden base and hand support, and a lever and cam for removing the pressure from the finger. The general construction will be clear from the accompanying cut. In the larger diagram, *A* is the pan of the scale, *B* its arm, *C* the lever, and *D* the cam.

The tips of the fingers are thrust into a horizontal opening in the left upright board of the frame, which is shown

[1] *American Journal of Psychology*, III., 1890–91, 54 f.

in front view in the small diagram at the right. In the same diagram is also shown the hard rubber knob on the end of the scale arm, which presses upward against the finger when the pressure stimulus is being applied. This is counterbalanced by a bit of wire attached to the framework under the scale pan, or by a piece of felt laid on top of the pan. The finger-rest and the end of the scale arm are also shown in section in the small diagram at the left. The stimulus weights are placed in the scale pan *A*, and



exert an upward pressure on the finger, but of reduced amount because acting upon the short arm of the balance—one-quarter their actual weight in the Clark instrument. Depressing the lever arm of the cam raises the latter, and allows the knob to reach and press upon the finger; raising the lever arm removes the pressure. The chief advantages of the instrument are the ease and precision with which the stimuli are applied and removed, and the unconstrained position of the hand of the subject.

A Minimal List of Apparatus.

It is hardly possible that any who use this course will wish to try all the experiments or require all the apparatus. Each one ought to examine the experiments for himself, choose what he is most interested in, and make up an apparatus list accordingly. It is therefore with some doubt as to whether a minimal list will be a really helpful thing that the author offers the following as seeming to him the most important pieces: weights for pressure and lifting, including those of equal weight but unequal size; a sonometer; ten or a dozen ordinary tuning-forks of a' and c'' pitches for special tuning (by careful filing, a heavy fork of a' pitch may be reduced to c', and give the octave with c''); a resonance bottle; a pair of bottle whistles; a yard of small rubber tubing; a color-wheel, colored papers, black and white cardboard for disks and diagrams; some small pieces of colored gelatine; a 60° prism; a dark box; a Wheatstone stereoscope convertible to a telestereoscope; a small set of drawing-instruments; and a couple of yards of metric cross-section paper.

Such a list includes several pieces that may be made at home, and ought not to cost more than twenty-five or thirty dollars. Makeshifts would often have to be used, and ordinary things about the room pressed into service, but with it a considerable number of experiments could be made. A large number of visual experiments are possible with the material included in Bradley's Pseudoptics; and if even the small list above is too expensive, that may be substituted for the color-wheel, the Wheatstone stereoscope, and most of the materials for disks and diagrams.

APPENDIX I.

The Field of Regard and Listing's Law.

EXPERIMENT 172 requires a somewhat fuller understanding of Listing's law than can be gathered from Ex. 131 *b*, where the subject was previously treated. It has, therefore, seemed best to attempt a fuller exposition of it here.

Listing's law, as stated by Helmholtz, is as follows: "*When the line of regard passes from the primary position to any other position, the angle of torsion of the eye in its second position is the same as if the eye had come to this second position by turning about a fixed axis perpendicular both to the first and the second position of the line of regard.*"[1] On this principle rest two important corollaries: 1st, in movements from the primary position there will be no rotation about the line of regard; 2d, in movements from one secondary position to another there will be such rotation.

THE HEMISPHERICAL FIELD OF REGARD.

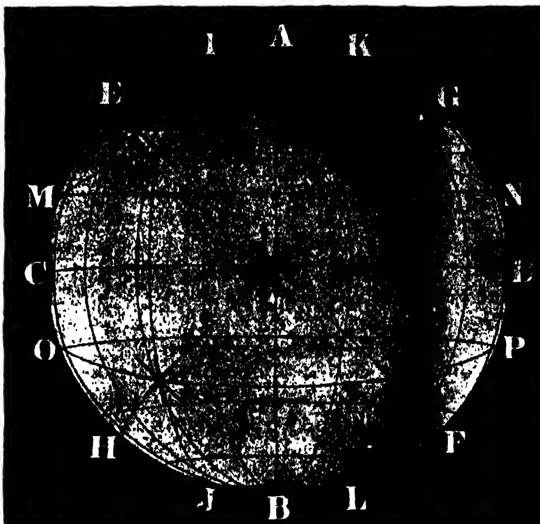
The usual way of putting the law to experimental test is to get a strong after-image of a rectangular cross on the centre of the retina, and then to observe the changes that its projected image undergoes as the eye is turned to one point and another of the field of regard. In the model from which the accompanying illustration is taken, an attempt has been made to show the changes that such an after-image would undergo when projected upon different parts of a hollow hemispherical field. The primary meridian of this field is *A* * *B*,[2] and other meridians are shown at intervals of 20°. The equator of the field (that is, the line of intersection of the plane of regard with the hemispherical field of regard when the eyes are in the primary position) is *C* * *D*, and above and below it are shown parallels at

[1] Helmholtz, Phys. Optik, 2te Aufl., p. 623, 1te Aufl., p. 466; Le Conte, Sight, 147.

[2] In naming the curves of the hemispherical field, the asterisk (*) is used for the central cross instead of a letter.

intervals as before of 20°. The eye itself is supposed to be at the centre of the sphere, i.e., in the plane of the letters *A*, *K*, *G*, *N*, etc., and at the centre of the circle that they mark.

Let us first illustrate the case of movements from the primary position. When the eye is in its primary position, it is directed forward and fixed upon the central eight-rayed cross. Imagine that the eye takes a lasting after-image from the cross, but first from the horizontal and vertical arms only. If the point of regard is elevated



or depressed in the primary meridian, and there is no rotation about the line of regard, the vertical bar of the after-image cross will still be found to lie in the meridian ; and if the point of regard be carried to the right or left in the equator of the field, the horizontal bar will still lie in the equator. This is shown by the slender crosses 40° from the centre on *A* * *B* and *C* * *D*. The axes about which the eye turns are evidently in the plane of the letters *A*, *K*, *G*, *N*, etc., and coincide in the first case with the (imaginary) diameter *C D*, and in the second with the (imaginary) diameter *A B*. Suppose now that the after-image has been taken from the oblique arms of

the central cross, and that the movement of the eye has been oblique to the right and upward, and to the left and downward along *H* * *G*, and to the left and upward, and to the right and downward along *E* * *F*, but without rotation about the line of regard. As before, those arms of the cross which originally coincided with these lines will be found to coincide with them after the movement, as shown by the corresponding arms of the slender crosses in these positions. The axis for movements in *G* * *H* lies in the (imaginary) diameter *E F*, and that for movements in *E* * *F* in the (imaginary) diameter *G H*. For any intermediate directions of movement, the axes would have a corresponding intermediate position; but in all cases the axes would lie in the plane of the letters *A*, *K*, *G*, *N*, etc., perpendicular to the line of regard both before and after its movement.

Since these after-images are always projected on a hemisphere, there is no distortion of any of the crosses due to projection on an oblique surface, and all of their parts maintain among themselves exactly the same relations that exist among those of the central cross.[1] It will be observed, however, that in the oblique positions the arms corresponding to the vertical of the central cross do not quite coincide with the meridians passing through the centres of the crosses, but make small angles with them, and that in the same way the arms corresponding to the horizontal in the central cross have no longer the same direction as the parallels above and below them. In other words, the vertical and horizontal arms appear to have rotated, though the fact that the oblique arms have maintained their coincidence with the circles *E* * *F*, and *G* * *H* shows that the rotation is not real, but as Le Conte says, "only an apparent rotation consequent upon reference to a new vertical meridian of space." This apparent rotation is known as *torsion*. The rule for this torsion is as follows: Movement of the eyes upward and to the right gives torsion to the right; upward and to the left, torsion to the left; downward and to the right, torsion to the left; downward and to the left, torsion to the right — all of which can easily be observed in the cut. Movements from any secondary position to the primary are evidently executed about the same axes as before, but in the contrary direction.

It remains to consider movements from one secondary position to

[1] This is true of the model after which the cut was made, but is not true of the crosses in the cut itself, which are obviously distorted because of just such a projection. This, however, does not affect the explanations that follow.

another. Let us start with an after-image from the slender cross on $C * D$, 40° to the right of the centre, and move upward along the meridian. The vertical arm of this cross coincides with the meridian at the start. When we reach the position of the eight-rayed cross, however, it no longer does so, but has turned slightly to the right — this time owing to a true rotation of the eye about the line of regard, and not to reference to a new meridian. The amount of rotation is small, in this case about 12°. Movement downward along the meridian would have exactly the same result, except that the rotation would be in the opposite direction, and similar rotations would be found if the cross 40° to the left of the centre on $C * D$ had been used for vertical movements, or the crosses 40° above and below the centre on $A * B$ had been used for right or left movements.

If movements from secondary positions along great circles produce this deviation of the arm of the cross from the line in which it moves, are there any lines to be found along which the eye may sweep the after-image without finding such a deviation? There are such lines, and four of them are shown in the figure. They are the arcs $I J$, $K L$, $M N$, and $O P$. It will be seen that these are drawn through the sloping positions of the arms of the side crosses on $E * F$ and $G * H$, and are perpendicular to $A * B$ and $C * D$ like the bars of their crosses. These are the Circles of Direction, or Right Circles, of Helmholtz (*Cercles de Direction*, *Richtkreise*[1]). The vertical circles of direction have, it will be observed, somewhat greater curvature than the meridians through the same points, and the horizontal circles of direction somewhat less than the parallels near which they lie. Along these circles a short after-image can be moved without leaving the line, a peculiarity in which they resemble a straight line, and when seen with the eye at rest under proper conditions they actually do appear straight. These circles have the further peculiarity that they all pass through the *occipital point*, a point as far behind the eye as the primary point of regard is in front of it. Both of these properties are shared also by all the great circles passing through the primary point of regard, so that they also are circles of direction. A circle of this kind, great or small as the case may be, can be passed through any two points in the field; they are not limited to those shown in the figure.

The mathematical study of Listing's law shows that the movement from one secondary position to another may, like those from

[1] *Op. cit.*, pp. 651 ff., 690 ff. (493 ff., 548 f.).

the primary position, be conceived as rotations about fixed axes all of which lie in a plane (though in this case the plane is not perpendicular to the line of regard), and that in every case there is also a line about which there is no rotation, the *atropic line*, though this does not coincide with the line of regard.

THE PLANE FIELD OF REGARD.

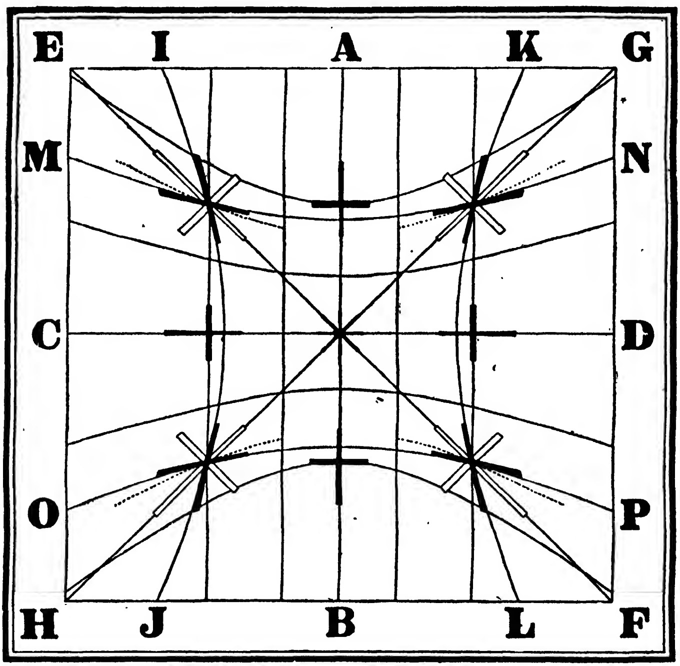
The experimental testing of Listing's law is generally carried out with the plane, instead of the hemispherical, field of regard, because of the difficulty of providing a large enough hollow hemisphere. But this has the disadvantage of adding to the changes in the after-image due to the movements of the eyes, a wholly new set of distortions due to the projection of the image upon an oblique surface. These are easily seen in the figure for the plane field.

This figure is a gnomonic projection of the hemispherical field upon a plane tangent to it at the middle point of the central cross. On this plane all the lines of the hemispherical field are represented exactly as their shadows would be cast by a point of light in the place of the eye, i.e., in the centre of the sphere. The meridians are represented by vertical straight lines, wider and wider apart as they are removed from the primary meridian *A B*. The parallels become hyperbolas, increasing in curvature as they are more distant from the equator of the field. The great circles through the primary point of regard are straight lines through the same point. The other circles of direction are hyperbolas. They maintain their resemblance to straight lines, however, in so far as concerns a short linear after-image moved along them, and are called by Helmholtz the *right lines* of the field of regard. The lettering of all the lines in the two figures is the same, so that comparison will be easy.

The distortion of the crosses on *A B* and *C D* is easy to understand, and also the oblique bars of those on *E F* and *G H* represented in outline in the figure. The arms corresponding to the vertical and horizontal arms of the central cross — represented in solid black in the figure — require a little explanation. If the matter were one of simple projection, without torsion, the arm corresponding to the vertical ought to coincide with the projection of the meridian, and that corresponding to the horizontal ought to coincide with the projection of a line, cutting the meridian at right angles in the hemispherical field, i.e., with the projection of the parallel that passes through the centre of the cross, — the dotted lines in the figure.

When these are regarded it is found that both arms of the cross show torsion as in the hemispherical field, though the distortion due to projection seems at first to have turned the two arms in opposite directions.[1]

This exposition has necessarily been physiological and geometrical. The psychological interest in the matter depends on the fact



that the perception of space with the eye at rest is profoundly affected by its experiences in or after motion, a large group of which are received while the eye is functioning in more or less accord with Listing's law. For a fuller account of these psychological matters, see Ex. 172.

[1] By an error in drawing, these solid black arms are placed beside the lines on which they should lie.

APPENDIX II.

Some Simple Cases of the Mathematical Horopter.

THE mathematical treatment of the horopter lies outside the scope of this work, but a geometrical description of some special cases may help to make the matter clear. Any such description must be based upon certain assumptions with regard to the distribution of corresponding points and the movements of the eyes. It is assumed in what follows, for example, that corresponding points in both eyes are so distributed that equal distances from the foveas in the same direction always give corresponding points, that there is no deviation of the retinal verticals (cf. Ex. 209 *b*), and that in movements with parallel lines of regard the eyes follow Listing's law, while in convergence, they rotate about the line of regard as observed in Ex. 133. The special cases taken for description are those arising with parallel lines of regard, and with convergence in different positions of the plane of regard.

THE HOROPTER WITH PARALLEL LINES OF REGARD.

Imagine lines of direction drawn from all the corresponding points in both eyes through the respective crossing points of lines of direction and continued to infinity. The points seen single must lie at the intersection of corresponding lines of direction. When the lines of regard are parallel and the eyes are unrotated, all these corresponding lines are parallel, i.e., meet at infinity, and the horopter will, therefore, be a hemisphere of infinite radius, or what amounts to the same thing, a plane at an infinite distance perpendicular to the lines of regard.

This is true whether the lines of regard are in the primary or in a secondary position, for so long as the eyes take their positions according to Listing's law, no rotation of the eyes about the lines

of regard is required, and the corresponding lines of direction remain continuously parallel.[1]

THE HOROPTER WHEN THE LINES OF REGARD ARE CONVERGED IN THE PRIMARY POSITION FOR CONVERGENCE.[2]

The horopter in this case is the major part of a circle passing through the crossing points of the lines of direction in the two eyes and a perpendicular to the circle at the fixation point.

It is not difficult to show that this is so, if use is made of a few retinal land marks. Imagine the eyes directed straight forward with parallel lines of regard. A plane passed through both lines of regard will cut the retinas in their *horizontal meridians* or *retinal horizons*. Planes passed through the lines of regard perpendicular to the plane of regard will cut the retinas in their *vertical meridians* or *retinal verticals*. These lines are the landmarks needed. In the present case the planes of the retinal horizon will coincide with the plane of regard, and the planes of the retinal verticals will be perpendicular to that plane and intersect in a line perpendicular to it at the fixation point.

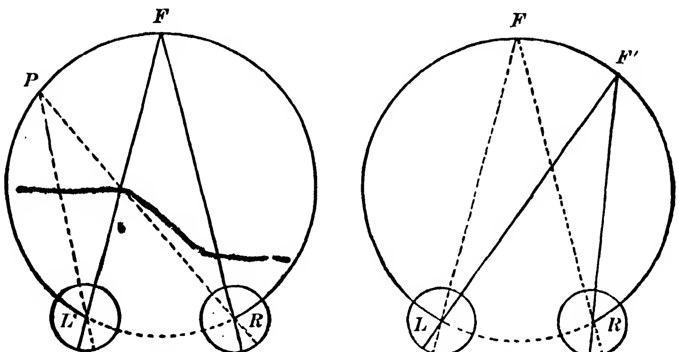
In Fig. *A* the letters *L* and *R* mark the crossing-points of the lines of direction in the two eyes; *F* is the fixation point; *LF* and *RF* mark the intersection of the planes of the retinal verticals with the plane of regard (and are thus also the lines of regard); the plane of the paper is the plane of regard. The horopter is composed of the circle *FRLP* (except the part *RL* between the eyes), and the perpendicular is a perpendicular to the plane of the paper at *F*. The circle is known as the "Circle of Müller," and the perpendicular (less frequently) as the horopteric line.[3]

[1] This may seem to contradict the statement on p. 424, that such rotations are present in movements from one secondary position to another; but the contradiction is only apparent, for the rotation in such cases is a rotation *with reference to the condition of the eye in its secondary starting-point*, and not with reference to its primary position. Even if there were rotation, the statement in the text would hold, for since the lines of regard are parallel, the degree of rotation would be the same in both eyes.

[2] The primary position for convergence is that depressed position of the plane of regard in which convergence is possible without rotation of the eyes about the line of regard. (Cf. Ex. 133, p. 126.)

[3] Footnote 1 on p. 271 states that the Circle of Müller lies in the plane of regard when the eyes are in the "primary position." This is the case only when "primary position" is understood in the sense of "primary position for convergence."

It is easy to show that the points of the circle will be projected on corresponding points of the retinas. Both retinal images of the point P, for example, lie on the retinal horizons, and both lie at equal distances to the right of the foveas, because the angle PLF is equal to the angle PRF, both being measured by half the arc PF. Any point inside of Müller's circle, including the part of the circle itself between L and R, will give heteronymous double images, and the points outside, homonymous images. The same will be true of any points, lying above or below the plane of regard, which lie also inside or outside of a cylindrical surface erected on this circle perpendicular to that plane. The perpendicular at F is clearly in the



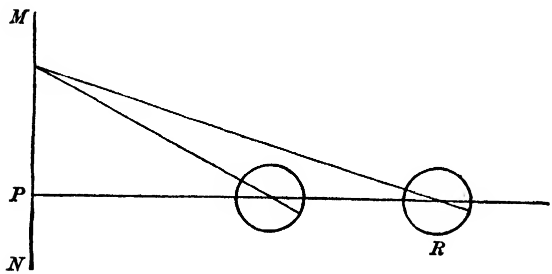
A B

horopter because its images will lie on the vertical meridians of both eyes, and every point of it will give an image equally distant from the fovea on that meridian in each eye. Other perpendiculars to Müller's circle, e.g., one at P, contain but a single point each that belongs to the horopter (the point in which they touch the circle), because, being unequally distant from the two eyes, all other points have images that lie at different distances above or below the retinal horizons.

This will be clear from the figure below. The image of every point on the line MN must fall on disparate points in L and R except that of the point P, for in every case the angle in the left eye will be greater than in the right. The same will be true of perpendiculars to the portion of the circle at the right of the fixation

point, except that the angle would then be greater in the right than in the left.[1]

When the convergence is asymmetrical the horopter remains exactly the same, the perpendicular lying not at the fixation point, but in the median plane of the head, as it did for symmetrical convergence. In Fig. *B* above, *F′* is the asymmetrical fixation point. The horopter is Müller's circle *RF′FL*, with the exception of the part *RL*, and the perpendicular is at *F*. The reasons for this can easily be gathered from what has already been said.



THE HOROPTER WHEN THE LINES OF REGARD ARE CONVERGED IN OTHER THAN THE PRIMARY POSITION FOR CONVERGENCE.

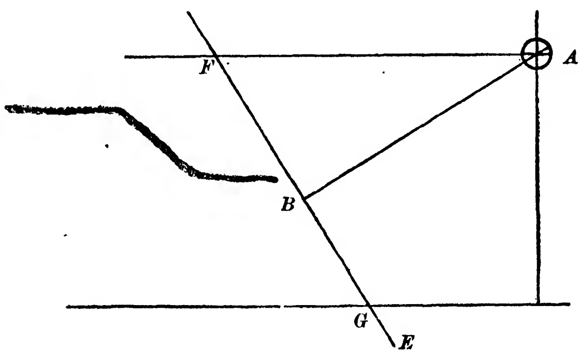
When the eyes are converged symmetrically, and the plane of regard is higher than in the case just considered (that is, in the vast majority of cases), convergence is attended by outward rotation of the eyes about the line of regard, the right eye rotating to the right and the left eye to the left. The horopter is consequently altered in form. The horopteric line is no longer perpendicular to the plane of regard, but inclines backward from the face of the observer. The reason for this inclination will be clear if the reader returns to the planes passed through the vertical meridians of the eyes, and imagines their rotation outward. The horopteric line is the line of intersection of these planes; and as the eyes rotate outward, the line of intersection rotates backward about the fixation point.

The rotation of the eyes also breaks up the coincidence of the planes of the retinal horizons with each other and with the plane of

[1] Ex. 210 *c* may seem to show something different, but the conditions there are such as to prevent the observation of images doubled vertically.

regard; a horopteric circle in that plane is therefore impossible. But as the eyes rotate, other pairs of corresponding planes (passing through the same horizontal axis of the eye but inclined downward) fall together. The planes that coincide are always perpendicular to the inclined horopteric line, and in them the horopteric circle lies. It does not, of course, cut the horopteric line in the fixation point. This form of the horopter is represented in the following cut.

The plane of the paper is the median plane of the head. *FA* represents the intersection of the plane of regard with the median plane. *DE* is the inclined horopteric line. *AB* is the intersection of the plane of the horopteric circle with the median plane. In ordinary vision the rotation of the eyes is very small, and the plane of *AB* is so little depressed below the plane of regard as to be practicably indistinguishable from it.



When the convergence is asymmetrical and the plane of regard other than the primary one for convergence, the horopter becomes a curve of double curvature, lying in the surface of a circular cylinder, and too complicated for easy exposition in this way. The following, from Hering's *Beiträge zur Physiologie* (p. 228 f.) shows the relation of this curve to the forms of the horopter just considered: "The horopter, made up of the circle and straight line, may be regarded as a curve of a single branch, which comes as a straight line from infinity, suddenly makes a right-angular turn, passes then as a circle through both crossing-points of lines of direction, and having returned to the point of inflection, makes another right-angular turn

and then continues, once more as a straight line, to infinity in a direction opposite to that from which it came. The horopter curve at other times also takes a closely similar course. It comes from infinity with very slight curvature on the surface of the cylinder in question, suddenly makes a more or less blunt turn, goes on, approximately in a circle, though always with double curvature, through both crossing-points, returns thus nearly to the first turn, makes, without touching it, another blunt turn, and runs once more with slight curvature to infinity in a direction opposite to that from which it came. The former right-angular turns with points in contact, in this case, are, as it were, drawn apart."

For a diagram showing the same in graphic form, see Helmholtz's *Physiologische Optik*, 2te Aufl., p. 861 (p. 714 of the first edition).

PLATE I.

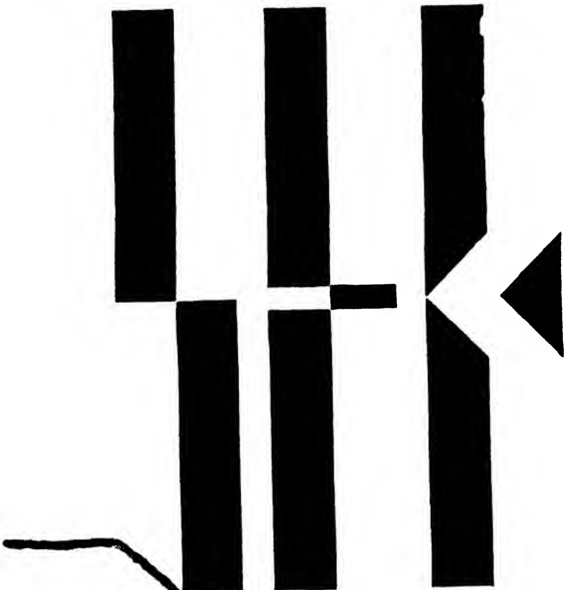
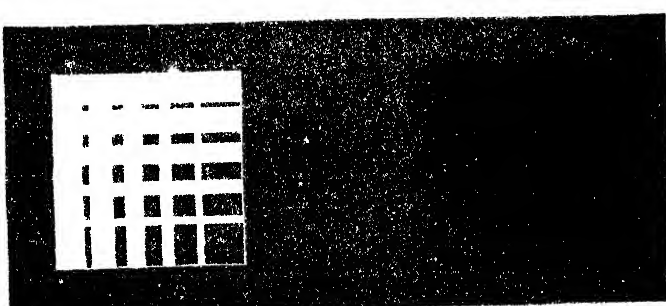


Fig. 1 Fig. 2 Fig. 3



Ex. 7. For systematic determinations, use an adaptation of the method of minimal change explained in Exs. 24 and 237.

17. The insertion of the second finger must be delayed till the sensation in the first finger has developed fully, but not until the physiological zero has shifted.

18*a*. If this experiment is to be conclusive, sufficient time must be allowed for change in the actual temperature of the finger brought from the hotter or colder water.

23. In the form here given this experiment is of little value, and may well be cancelled. In order to be comparable with cases apparently similar (Exs. 17 and 143*b*), it is necessary that the weight per unit area of surface should be the same. If this is so, the result would probably be reversed. Care must be taken to choose a surface for experiment that will allow the larger weight to touch over its entire surface.

35. This experiment as described depends on the determinations reached in Ex. 34 *b*, but this is unnecessary. It is simpler and better to furnish the subject with equal weights, one in either hand, and to require him, after lifting them alternately, to announce which seems the lighter. This may then be taken as the "standard," and the other as "the weight to be compared," for which the 2 kg. weight is later substituted, and the experiment continued as explained in the text.

36. It should be more distinctly stated in this case that the explanation in favor of innervation sensations is in the nature of a quotation, and does not represent the writer's opinion.

44*b*. For "millimeter scale" read "meter stick."

d. This experiment fails frequently with the operator seated; better results would possibly be reached by making the experiment while he is standing.

101*d*. This experiment should be made with unison forks.

111*b*. The movement of the candle should be of small extent — an inch or two perhaps.

c. The card must be held as close as possible to the eye.

116. This experiment will be easier if tried with the single eye.

117*a*. The way of finding the least distinguishable visual angle given in this experiment, and the inferences from it as to the size of the perceiving elements of the retina, are discredited, and the experiment should be cancelled.

The data for calculating the visual angle given in line 9 should read, "about 7 mm. back of the cornea and 15 mm. in front of the retina," instead of as given.

P. 119. Introduction to experiments on eye movements. The definition of the field of regard should be made to read: "*The Field of Regard* is the extent of space within which the Point of Regard may be moved without head movements."

Ex. 134. Unless the head is fixed in this experiment, involuntary movements of it may complicate the results.

145*c*. The flickering observed may be due to other causes than that suggested, and the experiment should therefore be cancelled.

147. In this experiment a greater blackening of the black sectors is to be observed when attention is so directed, as well as a brightening of the white. The brightness of such an object would appear to be judged, when attention is indifferent, from the brightness of its brightest parts.

150*a*. (Diagram, p. 151.) The arrangement shown does well enough if the background is white. If it is black, gray fields should take the place of the white.

152*a*. Cancel the second paragraph, with reference to the superior brightness of the yellow shadow.

d. Second paragraph, top of p. 159. The approach of the white card cuts off a part of the inducing color, and this may account for the effect, in which case the experiment would be of no importance for the theory of contrast.

154*a*. The statement made at the end of the paragraph, with reference to the absence of a dark halo surrounding the after-image of a black square on a white ground, is apparently an error. If this is the case, the whole of *a* loses special interest for the theory of contrast.

191*d*. The experiments of Pierce, published since this paragraph was written (*Psychological Review*, 5. 1898, 233–253), have demonstrated that the illusion in this figure is due to irradiation. It should therefore be omitted here and considered with the other irradiation figures in Ex. 235.

INDEX OF AUTHORS.

[When the same work has been cited in the bibliographies of more than one chapter the repetitions have been placed in parentheses.]

INDEX OF SUBJECTS.